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Filtikakis, Stefanos

Monterey California. Naval Postgraduate School

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PERFORMANCE ANALYSIS OF IEEE 802.11G SIGNALS UNDER DIFFERENT OPERATIONAL ENVIRONMENTS

by

Stefanos Filtikakis

September 2005

Thesis Advisor: Tri T. Ha
Second Reader: David C. Jenn

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The purpose of this thesis was to implement, analyze and evaluate the performance of an outdoor point-to-point 802.11g WLAN under different operational environments. The implementation was achieved using two low-cost commercially available wireless bridges and directional external antennas from a well-known manufacturer, Cisco. As part of the analysis, the effective throughput of this standard, the packet error rate and the received signal strength were measured in each of the following three environments: suburban area, medium density vegetation, and coastal. The signal path loss was then calculated from the recorded results and was compared to theoretical results from common outdoor propagation models. A new path loss exponent, n, was also estimated for each case. Based on this exponent, the free space path loss model was properly modified in order to fit the measured path loss results.

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PERFORMANCE ANALYSIS OF IEEE 802.11G SIGNALS UNDER DIFFERENT OPERATIONAL ENVIRONMENTS

Stefanos Filtikakis
Lieutenant Junior Grade, Hellenic Navy
B.S., Hellenic Naval Academy, 1998

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September 2005**

Author: Stefanos Filtikakis

Approved by: Tri T. Ha
Thesis Advisor

David C. Jenn
Second Reader

Jeffrey B. Knorr
Chairman, Department of Electrical and Computer Engineering

Dan C. Boger
Chairman, Department of Information Sciences

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ABSTRACT

A modern military environment requires flexible, capable and robust communications systems. Wireless communications infrastructures can provide all these services that are absolutely necessary to the soldiers on the battlefield or to the mission planners. The IEEE 802.11g wireless LAN seems to fit the military needs since it can provide data rates up to 54 Mbps and it is backward compatible with the earlier 802.11b specification.

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EXECUTIVE SUMMARY

The IEEE 802.11g specification is considered to be a harmonized combination of the earlier non-compatible specifications, 802.11b and 802.11a. The fact that it utilizes the 2.4 GHz band, as the 802.11b, and that it can provide theoretical high data rates up to 54 Mbps, as the 802.11a, has made it particularly popular in the market. This specification, therefore, is an attractive solution to the military requirements for deploying portable, low-cost and rugged wireless network infrastructures.

This thesis implements an outdoor point-to-point 802.11g wireless LAN and tests it under three different operational environments in order to evaluate its performance in these conditions. Since the need for high data rates is crucial, the research focuses on measuring the actual throughput of the deployed WLAN and comparing the results to the theoretical data rates. The evaluation also includes measurement of the packet error rate and the received signal strength at selected locations. An additional objective is to calculate the signal path loss in each environment and compare it with the results that are predicted from common outdoor propagation models.

First, the fundamental characteristics of the 802.11g, such as radio frequency channels, modulation schemes, performance issues, and security mechanisms, are briefly discussed. Second, there is a presentation of the selected wireless equipment that was used for the implementation of the WLAN. The goal was to use relatively low-cost, commercially available, and easy to transfer hardware. The Cisco Aironet 1300 Series Access Point/Bridge was chosen since it met these requirements. The basic components of the designed outdoor point-to-point wireless network were two wireless bridges and two external 13.5 dBi or 10 dBi Yagi directional antennas. The first wireless bridge was configured in the root role while the other one was configured in the non-root role. Additional equipment such as two portable power units and two laptops were used for the implementation of the network, while tools such as a GPS receiver, file transfer protocol software, and the graphical unit interface of the bridges were used for the performance analysis of the network.

Next, the implementation of the outdoor point-to-point 802.11g WLAN and the measurements in each operational scenario are presented. The measurements were conducted in the suburban area of Monterey with line of sight conditions, in a medium density vegetation environment on Fort Ord with non line of sight conditions, and in a coastal environment (along the Monterey Bay), again with line of sight conditions. The average results in all cases showed that for the data rates from 1 Mbps to 18 Mbps the effective throughput always ranged between 50 % − 70% of the corresponding theoretical data values. In fact, although the distance was increased, the results for these data rates did not degrade considerably. On the contrary, the data throughput for the 802.11g rates from 24 Mbps to 54 Mbps was found to be between 30 % − 40% of the corresponding theoretical data values and higher deviations were observed as the distance increased. It was also found that the average packet error rate increased as the distance between the two bridges increased.

The nature of each environment certainly affected the received signal strength results. The recorded values depended on the separation distance between the two wireless bridges as well as on the effect of multipath fading. The results in the coastal environment were better than those in the suburban area, since the multipath effects were less. The vegetation environment with non line of sight conditions had a great impact on the signal strength. The results were only acceptable for close distances to the root bridge.

Finally, the signal path loss was calculated from the recorded signal strength results. Using the measured path loss values and the free space model, an average path loss exponent, n, for each environment was estimated. These values confirmed the received signal strength performance in each environment: 2.08 for the suburban area, 3.71 for the medium density vegetation environment and 1.88 for the coastal environment. Moreover, depending on the operational scheme, the measured values were compared with the predicted path loss values from common propagation models.

I. INTRODUCTION

This chapter provides some general information about wireless LANs as well as the objectives and the outline of this thesis.

A. COMPARISON OF WLAN AND LAN

Over the past ten years the world has become increasingly mobile. As a result, the traditional wired networks that have been successfully used up to now seem to be inadequate in their ability to meet the challenges of the modern world. Wireless Local Area Networks are a relatively new form of local networks that allow users to be connected and communicate without the need of appropriate wiring. Wireless networks offer several important advantages over fixed (or wired) networks, no matter how the protocols are designed, or even the type of data they carry [1]:

- Mobility: It is the first and probably the greatest benefit of wireless networking. Mobility offers users the ability to freely roam within a wireless cell with connectivity to existing networks. Hence, they have access to real-time information wherever they are, which means that wireless networking provides more services and more productivity than wired networks.
- Ease and speed of deployment: WLANs do not require running cables through walls or ceilings, and they can be installed in places that are very difficult to carry out new local area networks.
- Flexibility: Wireless networking allows users to quickly form small group networks for the needs of a meeting and makes moving between the offices of a building a snap. Since the wireless network medium is available everywhere, the expansion of wireless networks is easy and quick.
- Cost: In some cases, costs can be reduced with the use of wireless networks. Although the initial investment could be expensive due to the equipment, in the future a wireless network will have a negligible monthly operating cost. More so, as this technology develops, new products are being presented, with better performance and lower cost.

Despite the above advantages, WLANs seem to have some limitations compared to wired networks, which can be summarized in the following [1, 2]:

- Throughput: Wireless network hardware tends to be slower than wired hardware. Although a great increase in the data rate has been noticed recently, the difference still remains considerable. The speed of wireless networks is constrained by the available bandwidth. Unless the regulatory au-

thorities are willing to make the unlicensed spectrum bands bigger, there is an upper limit on the speed of wireless networks.

- Interference and Reliability: Radio waves can suffer from a number of propagation problems that may interrupt the radio link, such as multipath interference and shadows. Unlike wired channels that are stationary and predictable, radio channels are extremely random and do not offer easy analysis.
- Data Security: It is absolutely a significant issue in wireless technology because the wireless medium cannot be controlled. Anonymous attackers can perform sniffing using simple equipment. In order to address this problem, encryption algorithms are being used during the transmission of the data, which increase the cost and reduce the actual throughput of the wireless system.
- Battery Power Consumption: In order to take advantage of the mobility of wireless networking, wireless users have to use mobile stations such as laptop computers or PDAs. Since these devices work with batteries, they need to have features to reduce power consumption while not using the network.

B. APPLICATIONS OF WLAN

Until relatively recently, WLANs were used sparingly because there were cost issues, low data rates, occupational safety concerns, and licensing requirements. As these problems have been addressed, the popularity of WLANs has grown rapidly [3]. Of course, this does not mean that WLANs are going to replace wired networks or make them obsolete. The basic applications of WLANs are listed below [3]:

- LAN Extension: This application area is used to link the WLAN to the backbone wired LAN. Examples of this application include buildings with large open areas, historical buildings, or small offices. In these cases, the WLAN saves the installation cost of LAN cabling and eases the task of relocation or extension of the wired LAN.
- Cross-Building Interconnection: WLAN technology is used for connecting LANs in nearby buildings. In these applications, a point-to-point wireless link is used between two buildings and devices such as bridges or routers are used.
- Nomadic Access: WLANs can be installed in public places or buildings where users are constantly moving and wish to access the wired LAN of the organization that they currently belong to.
- Ad Hoc Networking: An ad hoc network is a peer-to-peer network set up temporarily to meet some immediate need. The advantage of these net-

works is that the users can interchange data within the temporal networks without the need of prior installation or preparation.

The above applications of WLANs are quite obvious to most, since the use of laptop computers or other personal devices with wireless technology is a routine event experienced by many people in today's world. As far as the military is concerned, wireless technology seems to fit their need for temporary network infrastructures that are rugged, flexible and portable. In the modern battlefield for example, wireless technology can be used in order to provide useful and crucial data to soldiers on the battlefield and mission planners at headquarters, such as maps of surrounding terrains or the exact position of other soldiers [4].

C. SCOPE OF THESIS

The most prominent specification for wireless LANs was developed by the IEEE 802.11 working group. Like many standards, 802.11 has gone through many iterations and expansions over the years. The IEEE 802.11g version of the wireless family of technologies was approved and formally sanctioned in June 2003. This standard was based on the existing 802.11 WLAN protocol, which was originally released in 1997. The interesting thing is that it takes advantage of the physical layer techniques designed for 802.11a to provide much higher data rates in the 2.4 GHz band [5, 6]. It offers theoretical transfer rates from 1 Mbps to 54 Mbps and can provide backwards compatibility with existing 802.11b networks. The performance of this standard, as well as all other wireless systems, depends on the interference effects and propagation environments.

The initial objective of this thesis study was to implement and test an outdoor point-to-point 802.11g WLAN using external directional antennas under three different operational environments in order to examine whether this standard could actually be used for military operations or other applications. Additional goals were to measure the actual throughput of this standard and the Packet Error Rate (PER) in each of the three environments. The last objective included the comparison of the measured signal path loss results that were derived from the different operational scenarios to the ones that are predicted from commonly used outdoor propagation models.

D. THESIS OUTLINE

This thesis is organized as follows. Chapter II gives an overview of the IEEE 802.11 Standard and its current specifications. Chapter III presents the selected equipment that was used in order to implement and analyze the performance of the outdoor 802.11g WLAN. In Chapter IV, the initial setup and configuration process of the wireless bridges is described.

Chapter V covers the implementation of the outdoor 802.11g WLAN in three different operational environments and provides the results of the conducted measurements in each case. These results include the achievable throughput of the standard, the PER and the received signal strength for each test location in a suburban area environment, a medium density vegetation environment and a coastal environment. Chapter VI refers to some common outdoor propagation models and compares the predicted path loss results from these models with the results that were derived from the field measurements. Chapter VII summarizes the results of this thesis and suggests topics for future research.

II. THE IEEE 802.11 STANDARD

A. OVERVIEW OF THE IEEE 802.11 STANDARD

In 1990, the Local and Metropolitan Area Networks Standards Committee (LMSC) formed the 802.11 workgroup to begin developing a wireless standard. The first IEEE wireless standard, which was completed in 1997, provided a mandatory 1 Mbps and an optional 2 Mbps data transfer rate using the 2.4 GHz Industrial, Scientific and Medical radio band. The 2.4 GHz radio band was selected due to the fact that it was available for unlicensed use in most countries of the world [7].

The 802.11 standard defines the interface between wireless clients and their network access points. Its base specification includes the 802.11 Physical (PHY) and the Media Access Control (MAC) layers. In addition, the standard defines a basic security mechanism, called Wired Equivalent Privacy (WEP), and an outline of how roaming between access points should work [7].

The PHY layer for IEEE 802.11 defines the wireless transmission. Three physical media are defined in the original 802.11 standard: Direct-Sequence Spread Spectrum (DSSS) radio, Frequency-Hopping Spread Spectrum (FHSS) radio, and infrared. Both DSSS and FHSS radio operate in the 2.4 GHz ISM band at data rates of 1 Mbps and 2 Mbps, while infrared operates at a wavelength between 850 and 950 nm [3]. In 1999, the 802.11 workgroup, in order to increase the data rates, developed two other physical layers, which were based on radio technology: the Orthogonal Frequency Division Multiplexing (OFDM) and the High-Rate Direct Sequence (HR/DS or HR/DSSS) [1].

The IEEE 802.11 MAC layer performs the following three functions: reliable data delivery, access control, and security. The basic data transfer mechanism in the standard involves an exchange of two frames, while for enhanced reliability a four-frame exchange may be used. A MAC algorithm, called DFWMAC (Distributed Foundation Wireless MAC), provides a distributed access control mechanism with an optional centralized control built on top [3].

The 802.11 specification also specifies the optional use of encryption for security by means of the WEP feature. WEP is designed to provide confidentiality and authentication services, and is based on the RC4 algorithm. However, since WEP has not proved to be flawless, the IEEE has been trying to address the failures of WEP via a new task group, the 802.11i [7].

Standard 802.11 currently includes three specifications: 802.11a, 802.11b and 802.11g. The following section of this chapter will briefly cover the 802.11a and 802.11b specifications while the 802.11g specification will be more analytically described. Finally, the last section of the chapter will discuss some important security issues of the standard.

B. ANALYSIS OF THE IEEE 802.11 SPECIFICATIONS

The letters a, b, and g that accompany the name of the 802.11 workgroup indicate the chronological order in which each specification was proposed. Although 802.11a was proposed before b, the 802.11b specification was finished sooner than 802.11a, because it involved a more simple modulation technology [7].

1. The IEEE 802.11b Specification

The IEEE 802.11b specification was proposed in order to increase the data rates that were provided by the original 802.11 specification. In September 1999, the 802.11b was adopted as a standard for a high-speed connection to 802.11 and provided data rates up to 11 Mbps while still using the 2.4 GHz radio band [7]. Actually, this specification is an extension of the 802.11 DSSS scheme and is capable of providing two higher data rates, 5.5 and 11 Mbps. The chipping rate was kept the same (i.e., 11 MHz), which resulted in the same occupied bandwidth [3]. The 802.11b uses the Barker Code Direct Sequence Spread Spectrum with BPSK or QPSK modulation to transmit at 1 and 2 Mbps respectively, and Complimentary Code Keying (CCK) or Packet Binary Convolutional Coding (PBCC) to transmit at 5.5 and 11 Mbps [5].

The main advantage of the 802.11b specification is the fact that it uses the same frequency as the initial 802.11 standard. The use of the 2.4 GHz frequency makes the 802.11b signals less susceptible to degradation and more capable of covering larger areas.

On the other hand, since this frequency band is unlicensed, there is interference caused from other devices (e.g., cordless phones, microwave ovens) that operate in the same frequency [8].

The 802.11b wireless products have penetrated the worldwide market in a really successful and profitable way. Nowadays, the majority of deployed 802.11−based wireless networks are of the 802.11b variety. The price of the 802.11b wireless products has been significantly reduced as compared to their cost during the first years of their presentation in the market. Many terminal device manufacturers, such as laptop, PDA, and cell phone vendors, have integrated 802.11b chipsets directly into their devices [6].

2. The IEEE 802.11a Specification

The IEEE 802.11a specification differs from the other 802.11 group specifications in the sense that it uses a completely different radio band, the 5 GHz, and a new modulation scheme, the Orthogonal Frequency Division Multiplexing (OFDM). OFDM, which is also known as multicarrier modulation, "uses multiple carrier signals at different frequencies, sending some of the bits on each channel." [3] The interesting point about OFDM is that it does not use guard bands like the traditional Frequency Division Multiplexing (FDM) and hence prevents the waste of bandwidth and increases the capacity of a system [1].

One of the characteristics of the 802.11a is that it utilizes 300 MHz of bandwidth in the 5.0 GHz Unlicensed National Information Infrastructure (U-NII) band. This 300 MHz of bandwidth has been divided into three distinct 100 MHz sub-bands: the low (5.15-5.25 GHz), the middle (5.25-5.35 GHz), and the high band (5.725-5.825 GHz). Each of these sub-bands has four non-overlapping channels with unique power level settings that make it applicable for selected applications and the 5.0 GHz band offers less interference issues, since the majority of the wireless devices use the unlicensed 2.4 GHz ISM band. That is why 802.11a is considered to offer some additional "privacy" over the other two more popular specifications [6, 9].

This higher speed specification supports the following data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. These high data rates are achieved "by combining many lower speed subcarriers to obtain a high speed channel." [9] The 802.11a uses eight non-overlapping

channels across the low and the middle sub-bands, and each of these channels occupies a bandwidth of 20 MHz and is divided into 52 mutually orthogonal 300 KHz wide subcarriers. The subcarriers are modulated using BPSK, QPSK, 16-QAM or 64-QAM, dependent on the selected data rate of transmission. For each one of the eight non-overlapping channels, the 52 subcarriers are transmitted and received at the same time. Finally, at the receiver, the "slow" signals are multiplexed to provide the "fast" actual signal [3, 9].

3. The IEEE 802.11g Specification

The 802.11g standard was expected with great anticipation by the wireless product industry. It was approved in June 2003 and since then there have been many new products in the market from different manufacturers that are based on this advanced standard. There are two advantages to this specification. First, it can provide high data rates up to 54 Mbps in the 2.4 GHz band. Second, it is fully backwards compatible with the popular 802.11b standard.

a. 802.11g in Brief

The 802.11g WLAN standard can be considered to be something like a "combination" of the two earlier standards of the 802.11 workgroup, the 802.11b and 802.11a. The similarity with the 802.11b is that it uses the same portion of the radio frequency spectrum, the 2.4 GHz unlicensed band. Internationally in this band there are 14 standard 22 MHz channels, which are spaced at 5 MHz intervals [5]. The 802.11g uses 13 out of 14 channels. In Table 1 below, the center frequency as well as the frequency spread for each one of the 13 channels is shown.

802.11g Radio Frequency Channels		
Channel	**Center Frequency (MHz)**	**Frequency Spread (MHz)**
1	2412	2401−2423
2	2417	2406−2428
3	2422	2411−2433
4	2427	2416−2438
5	2432	2421−2443
6	2437	2426−2448
7	2442	2431−2453
8	2447	2436−2458
9	2452	2441−2463
10	2457	2446−2468
11	2462	2451−2473
12	2467	2456−2478
13	2472	2461−2483

Table 1. Channels for IEEE 802.11g (After Ref.10.)

In the United States, only channels 1 through 11 are legal and 802.11g is limited to only 3 non-overlapping channels (i.e., channels 1, 6, 11) just like 802.11b. If an overlapping channel is assigned then there is the potential for inter-carrier interference. The result will be an increased noise floor in this channel, and therefore the throughput and the effective range of the system will be negatively affected [5].

The 802.11g uses a combination of OFDM and DSSS transmission techniques to provide a large set of data rates, and actually supports both the data rates of 802.11b and 802.11a. Hence, it is capable of providing 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48 and 54 Mbps. Of these data rates, the transmission and reception capability for 1, 2, 5.5, 11, 6, 12 and 24 Mbps is mandatory [11]. The 802.11g is therefore a balanced compromise standard since it offers a much clearer "bridge" between 802.11a and 802.11b.

Not only does it achieve the high 54 Mbps data rate of 802.11a in the 2.4 GHz, but it also maintains compatibility with the current installed 802.11b WLANs. Table 2 contains the supported data rates of the standard, as well as the transmission type and the modulation scheme for each of the data rates.

Data Rate (Mbps)	Transmission Type	Modulation Scheme
54	OFDM	64 QAM
48	OFDM	64 QAM
36	OFDM	16 QAM
24	OFDM	16 QAM
18	OFDM	QPSK
12	OFDM	QPSK
11	DSSS	CCK/PBCC
9	OFDM	BPSK
6	OFDM	BPSK
5.5	DSSS	CCK/PBCC
2	DSSS	QPSK
1	DSSS	BPSK

Table 2. The 802.11g Data Rates and Modulation Methods (From Ref. 10.)

b. 802.11g Performance Issues

There has been a lot of discussion about the actual data rate, better known as throughput, of the wireless systems. Although the 802.11 workgroup has theoretically announced the data rates for each one of its specifications, in practice, the actual achievable throughputs are lower than the "advertised" ones. This of course does not only happen with the 802.11g standard, it occurs with all the IEEE 802.11 standards. Since wireless networks use the air interface, the 802.11 design committee had to build some mechanisms into the protocol in order to ensure that the channel will be used fairly and that the data will be delivered to the users across the air medium with certainty. The protocol that was designed for this fair access is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [6].

This protocol is similar to the one that was used in 802.3 (i.e., Ethernet LANs), known as Carrier Sense Multiple Access with Collision Detection (CSMA/CD). The difference is that in wireless communications, when a collision happens, it goes undetected. For this reason, a collision between packets is always assumed, unless the stations are somehow notified that it did not happen. Thus the receiving station always sends an acknowledgement message (ACK) to the transmitting station to prove that it did in fact receive the wireless data packets. In cases where the transmitting station does not receive this ACK in a specific amount of time, it assumes that a collision has occurred, the data packet was lost, and hence retransmits the data [6]. This overhead, as well as the distance and the nature of the environment between the wireless client and the access point, have an impact in the actual performance of each WLAN. According to [12], in an environment where there are no other radio devices operating and the wireless client is close to the access point, one should expect that the actual achievable throughput will be approximately 50% lower than the higher data rate.

Another important factor that significantly affects the throughput provided by 802.11g networks is whether or not they are supporting 802.11b clients. The 802.11g standard provides protection mechanisms to ensure coexistence and backward compatibility with the 802.11b standard. A protection mechanism called Request to Send/Clear to Send (RTS/CTS) is invoked each time that 802.11b clients are associated to an 802.11g access point, which is the case of a mixed-mode network. This mechanism, in simple terms, precludes the 802.11b clients from transmitting simultaneously with 802.11g clients. Hence, collisions that decrease the throughput due to retries are avoided. However, this additional protection mechanism has a negative result in the network throughput because it adds a significant amount of protocol overhead [13].

In addition to the above RTS/CTS mechanism, the 802.11g standard includes the “back-off time” requirement in order to provide 802.11b compatibility. Although collisions are greatly reduced due to RTS/CTS, in the event that one does occur, the client devices “stay away” from the network for a random period of time before they try a new attempt. The clients have to select this random time from a number of fixed duration slots. The “back-off time" is a multiple of the slot time and represents the random

length of time that a station waits before sending a packet on the LAN. When 802.11g networks operate in a mixed mode they adopt the 802.11b slot time (20 μs), while when they operate only in g mode they adopt the higher performance 802.11a slot time (9 μs) [13].

It would also be interesting to take a look at the throughput performance of 802.11g as compared to the 802.11a, since both standards use almost the same transmission technique, OFDM. One would expect that the actual throughput of the two standards, when they operate under the same conditions, would be the same. However, in reality, 802.11g throughput performance will be different from 802.11a. According to [14] this can be explained because of the following reasons:

- There are fewer available channels in the 2.4 GHz band than in the 5 GHz band. In the U.S., for example, there are only 3 non-overlapping channels for the 2.4 GHz ISM band, while for the 5 GHz U-NII band there are 12 channels. This difference has an impact on the capacity requirements and it is obvious that it favors 802.11a. The 802.11g will suffer from co-channel interference due to frequency reuse to a greater extent, since the available non-overlapping channels are fewer.
- A signal transmitted in the 2.4 GHz will carry further than a signal transmitted in the 5 GHz, which means that the propagation loss favors 802.11g because the free space path loss is less in the 2.4 GHz than it is in the 5 GHz. On the other hand, the unlicensed 2.4 GHz ISM band is a congested band since Bluetooth devices, cordless phones, microwave ovens, etc. operate in this band. Hence, 802.11g WLANs will probably encounter the problem of interference from these devices, which will certainly affect their actual performance.
- Since 802.11b and g operate in the same frequency, when both devices are present, the impact in the overall performance will be significant if there is no coordination between the b and g clients.
- As was mentioned above, the 802.11g adopts the 20 μs slot time of 802.11b in order to be compatible with it and only when the WLAN operates in the g mode does it adopt the 9 μs slot time of 802.11a.

As far as 802.11g is concerned, LT Georgios Kypriotis concluded in his research that "the 802.11g [client/access point] network could provide up to 20 Mbps of data link rate for distances up to 200 m while the data link rate degraded (1 Mbps or lower) at the range of 400 m." [10] In the following chapters of this thesis, it will be shown how an 802.11g outdoor WLAN was implemented with point-to-point link using

external directional antennas, and what the actual throughput values were when measured in three different environments.

4. IEEE 802.11n: The New Standard

In January 2004, IEEE announced that it had formed a new task group, 802.11n, in order to develop a new amendment to the 802.11 WLAN standards. This new standard builds upon the previous ones by adding Multiple Inputs Multiple Outputs (MIMO) antenna techniques. Using spatial multiplexing or spatial diversity, these techniques allow for greater coverage ranges and increased data throughputs. According to the initial announcements, this standard will be capable of providing at least 100 Mbps of actual data throughput and a greater operating distance than the current 802.11 standard [15].

5. Comparison of the Three Standards

Table 3 summarizes the basic characteristics for each of the three standards and provides an easy way of comparing them.

	802.11a	802.11b	802.11g
Standard approved	July 1999	July 1999	June 2003
Modulation Techniques	OFDM	Barker Code/ CCK/ PBCC	Barker Code/ CCK/ OFDM/ PBCC
Data Rates (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	1, 2, 5.5, 11	1, 2, 5.5, 11 6, 9, 12, 18, 24, 36, 48, 54
Slot time	9 μs	20 μs	20 μs 9 μs (optional)
Preamble	OFDM	Long/ Short (optional)	OFDM/Long/Short
Operating Frequencies	5−GHz U−NII/ISM Bands	2.4−GHz ISM Band	2.4−GHz ISM Band
Non−Overlapping Channels	12 (U.S.A)	3	3
Peak Speed	High	Medium	High
Capacity	High	Low	Medium
Range	Low	High	High
802.11b Compatible	No	Yes	Yes
Cost	Medium	Low	Low

Table 3. Basic characteristics − Comparison of 802.11a, b, g (After Refs. 10, 16.)

C. SECURITY ISSUES

Since the use of WLANs has been exponentially increased in the last decade, security concerns have become more and more intense. Because of its nature, wireless technology brings significantly more threats than wired networks. The most common threat that a wireless network is very likely to face is eavesdropping; where an anonymous attacker, who does not have to be a professional, uses simple equipment to passively intercept radio signals and decode the data that is being transmitted [7]. This simple example reveals how vulnerable, from a security aspect, WLANs can be and how important it is to use security mechanisms in the different 802.11 standards.

1. 802.11 Security Flaws

The Wired Equivalency Policy (WEP) provides the security for 802.11, at the MAC layer for authentication and encryption. WEP is based on the RC4 algorithm, which is also known as a stream cipher. The whole concept is based on generating a RC4 stream with a combination of a 24-bit initialization vector (IV) and a 40, 104, or 128-bit user-defined shared key. The IV is used so as to make the generated RC4 stream different each time. The data, before being transmitted, is XORed with the generated stream, and the result is a WEP frame that contains the IV in the header. After this frame is transmitted, the receiver generates the same RC4 stream, since it knows the IV and XORs the packet for decryption [7].

The implementation of WEP has caused problems. Today's tools and knowledge are such that it allows hackers to compromise a typical wireless network's WEP key. In 2000, a paper was published by researchers from the Berkeley University of California, which referred to the vulnerabilities of WEP and the ways that it could be compromised. Some of the most important flaws of the WEP include weak encryption, static encryption keys and a lack of a key distribution method [17]. Hence, "WEP can be used as a first line of defense, but cannot be relied on for security." [7] Additionally, it can be used in all cases where enhanced security is not required, either for commercial or military implementations.

2. 802.11 Security Enhancements

In order to improve the 802.11 standard security mechanisms, organizations such as IEEE, the Wi-Fi Alliance, Cisco Systems and Fortress Technologies have introduced some enhanced security solutions, which were developed around standard-based technologies. The IEEE's 802.1x Port Based Network Access Control standard provides strong authentication and network access control for 802.11 WLANs. The IEEE also set up a new task group, 802.11i, in order to replace the current security mechanism. The Wi-Fi Alliance announced an interim specification called Wi-Fi Protected Access (WPA), based on a subset of the current 802.11i draft. Finally, in June 2004, 802.11i (which is also known as WPA2) was ratified. This new security standard for 802.11

WLANs uses the Advanced Encryption Standard, instead of RC4, which was used in WEP and WPA [17]. Next, some of the 802.11 security enhancements will briefly be covered.

a. IEEE 802.1x

802.1x is a standard that provides authentication and authorization functions for networking access. It includes three components: the Supplicant (i.e., the wireless client), Authenticator (i.e., access point) and Authentication Server (AS). The most common type of AS is Remote Authentication Dial-In User Service (RADIUS), which is typically a stand-alone software package installed on a personal computer. Extensive Authentication Protocol (EAP) is used to authenticate the users, or in other words, to pass the necessary authentication information from the Supplicant to the AS. The session, which is effectively created, allows the wireless client to access the network only for authentication purposes. After the authentication process has been completed, the session is terminated and the wireless client is granted access [17].

For advanced data protection in a WLAN, both 802.1x and WEP can be used. In the case that 802.1x EAP supports mutual authentication (i.e., authentication from the wireless client to the AS and the opposite), such as the Cisco LEAP, the WEP keys are strongly improved by enabling dynamic rotation. This feature offers the advantage of the generation of new session keys when a session expires or the client roams from one AP to another, and therefore the generation of new WEP keys. This means that even if an attacker manages to intercept a WEP key, after a specific amount of time, he will not be able to use it because it will be invalid [17].

b. IEEE 802.11i Enhanced Wireless Security Standard

The 802.11i task group was formed to address the security vulnerabilities of the 802.11 standard, and includes strong authentication through the IEEE 802.1x as well as data encryption mechanisms through the Temporal Key Integrity Protocol (TKIP) and Counter Mode with CBC-MAC Protocol (CCMP). TKIP can be incorporated in current 802.11 wireless products since it will be available as a firmware or software upgrade. On the other hand, CCMP requires new 802.11 hardware with greater processing power

and increased memory, and is based on the Advanced Encryption Standard (AES). The Wi-Fi alliance started the certification testing for this standard in September 2004 [17].

c. Wi−Fi Protected Access (WPA)

In late 2002, the Wi-Fi Alliance introduced the first version of the Wi-Fi Protected Access (WPA) in order to fill the security gap until the ratification of the 802.11i standard. In practice, WPA is a subset of the 802.11i security and since the end of 2003 has become mandatory for the Wi-Fi certification of wireless products [17].

WPA uses the TKIP for strong data encryption, while for authentication and key management purposes it utilizes two different methods. The first authentication method is based on 802.1x and mutual authentication-based EAP, and takes place in enterprise environments that have a centralized authentication server. The second method is based on a Pre Shared Key (PSK) authentication and is used in more simplified environments, like a home or small office. In this case, the user has to manually enter a password (Master Key) in order to communicate with an access point, and this manually configured WPA password automatically starts the TKIP data encryption process [17].

The current version of the WPA (WPA2) has fully adopted the 802.11i security standard and provides security mechanisms for access point-based and ad-hoc (i.e., peer-to-peer) 802.11 infrastructures.

D. SUMMARY

This chapter provided a brief description of the IEEE 802.11 standard and its current specifications. It also included some important performance issues about the 802.11g specification, as well as its relation to the 802.11b and its differentiation from the 802.11a. Finally, the latest security mechanisms that support the 802.11 standard were briefly presented.

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III. 802.11 NETWORK DEPLOYMENT, EQUIPMENT AND RF ISSUES

This chapter will cover some important issues that are related to the successful deployment of an 802.11 wireless LAN and will also present the equipment that was adopted for the implementation and performance analysis of the outdoor 802.11g WLAN in the city of Monterey, California and its surrounding area. Finally, some radio frequency issues related to the 802.11 will be briefly described.

A. PLANNING AN OUTDOOR WLAN

Before purchasing the required equipment and implementing an outdoor WLAN, there must be appropriate planning in order to identify some important requirements. The following information is considered to be necessary for the planning of an outdoor WLAN [1]:

- Throughput Considerations: the purpose of using a WLAN and the type of hardware that will be used determines the needs for actual throughput in the WLAN.
- Coverage Area: one should have in mind how big the area is the desired area of coverage is, in order to buy the appropriate wireless equipment and determine the most appropriate points for installing it.
- User Population: it is obvious that the more wireless users there are, the more complicated and sophisticated the WLAN should be.
- Mobility: it is a crucial issue for both the business and military world. A WLAN engineer has to take into account the needs of the wireless clients for full mobility inside the coverage area of a wireless network or between different coverage areas of other WLANs.
- Site Environmental Considerations: this is also critical since the quality of service in a WLAN is greatly affected by the type of environment that the network is built in. Radio propagation and received signal strength depend on the operational environment; which is why a detailed site survey is necessary before the installation of the WLAN begins.
- Security Requirements: this is perhaps the most difficult part of the planning procedure. Each WLAN should provide authentication and encryption mechanisms. In some cases, such as in a military environment, where a high level of security is required, the wireless equipment that will be used should include the latest authentication and security mechanisms that are available in the market (i.e., 802.1x and WPA).

- Physical Network Considerations: it should be examined whether a WLAN can be deployed using various components of an existing wired LAN, such as cabling or power outlets. Additionally, one should also estimate the appropriate locations where an access point or a wireless bridge can be installed in order to better support the wireless clients in the WLAN.

Conducting a site survey before implementing an outdoor WLAN is very important, but even before attempting the site survey, it is useful to begin with a preliminary plan. For an outdoor WLAN, one can either use a map of the desired area to be covered, drive, or walk in order to find some trial access point/bridge locations. Hence, the purpose of the preliminary plan is to come up with appropriate test site locations that can be used later for a more advanced survey. In his research, Hsiung Wei Roy Chan conducted a preliminary check around the Naval Postgraduate School with a direct Line of Sight (LOS). From this check, he found out that a "direct LOS was critical and essential for IEEE 802.11a networks." [18] More generally speaking, for outdoor coverage, dense trees, buildings, hills and any other obstacle between the radio site and the service area should be noted. A good rule is to note how far away someone can physically see the radio site from as many locations within the desired service area as possible [5].

After the preliminary plan has been completed, the site survey can begin. At the selected site points, using different tools, the received signal strength of a wireless client can be determined. Most of the time, this can be achieved by the graphical unit interface (GUI) of the access point or the network interface card. The received signal strength is a major factor to determine whether the selected test point can actually be used for the installation of an access point/bridge, since it is a either a measure of indicating multipath interference, simply a wrong antenna type choice, or even a bad antenna installation at the transmitter or the receiver site. Therefore, the site survey can, in some capacity, discover any unforeseen interference problems and gives the opportunity of redesigning the network accordingly [1].

B. SELECTED EQUIPMENT FOR THE IMPLEMENTATION OF THE 802.11G OUTDOOR WLAN

The equipment that was chosen for the implementation of the 802.11g outdoor WLAN along with the architecture of the designed WLAN will be presented in this section. Several factors were taken into account for selecting the appropriate equipment. First of all, the implementation and testing of an outdoor 802.11g WLAN, which would cover as much area as possible around the city of Monterey under different operational environments was sought. There was interest in a temporary network infrastructure that would be rugged, flexible and mainly portable, as well as easy to install each time at different locations. This could be the case for remote military operations, or the extension of a wired LAN, or the point-to-point and point-to-multipoint interconnection of two or more buildings. The cost of the equipment should remain relatively low but the performance should be high enough to support the enhanced needs of either the military or business standards. What's more, the need for security options in the WLAN was important.

Having all the above in mind, the decision was made to implement and test a point-to-point configuration in different locations and under different environmental conditions, mainly because of the fact that a more advanced configuration would certainly require the work of more than one person. Hence, in order to accomplish the task, wireless equipment from a well known and industry leading manufacturer, Cisco, was selected and used. Cisco Aironet 1300 series Outdoor Access Point/Bridge was the choice since it met all specifications. This specific series can operate as an access point, a wireless bridge or a workgroup bridge [19]. For the needs of this research, the device was used exclusively as a wireless bridge. The choice was made to use external directional antennas with the bridge to achieve long coverage ranges and compare them with the advertised ones by Cisco.

The flexible and portable outdoor wireless bridge was provided through the combination of the Cisco Aironet 1300 series (802.11g interface), a power injector and options for both antennas and mounting [19].

1. Cisco Aironet 1300 Series Access Point/Bridge

The Cisco Aironet 1300 series is actually the 802.11g interface for either access point capability or bridge connections and can support legacy 802.11b clients, if required. In Figure 1, the unit can be seen, with the connectors for the external antennas and the power injector. The two antenna connectors that are provided on the end of the unit can support single or diverse antenna configurations. In the case of this thesis, a single antenna configuration at each point of the wireless LAN was used. It is also important to mention that mounted on the back of the housing of the unit are four LEDs that indicate the startup status, operating mode, association status and received signal strength. These LEDs, are used when activating the link and positioning the directional external antenna while at the bridge mounting location [19].

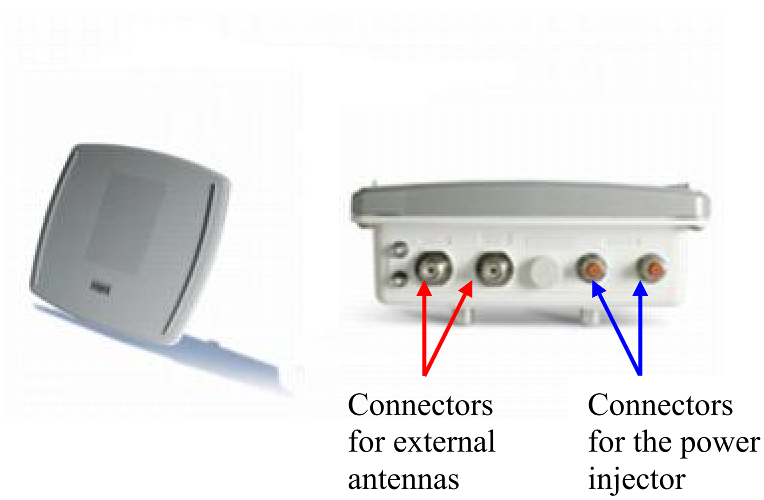

Figure 1. Cisco Aironet 1300 Series (802.11g Interface) (After Ref. 19.)

2. Power Injector

The power injector, which is shown in Figure 2, "converts the standard 10/100BASE-T Ethernet interface that is suitable for weather-protected areas to a dual F-Type connector interface for coaxial cables that are more suitable for harsh outdoor environments. The power injector also provides power to the outdoor unit over the same cables with a power-discover feature and surge protection." [19]

Figure 2. Cisco Aironet Power Injector (After Ref. 19.)

3. External Antennas

As was previously mentioned, the choice of the antennas for a WLAN is a very important issue. For the purposes of this thesis, the choice was made to use directional antennas so as to maximize the range of the WLAN. Cisco offers a variety of choices for 2.4 GHz and 5 GHz antennas, including both directional and omnidirectional options. The main characteristics of the selected 2.4 GHz antennas are summarized in Table 4 below. The omnidirectional antenna of 5.2 dBi was used for the initial setup of the two bridges in an indoor environment.

			
Feature	AIR−ANT2506	AIR−ANT2410Y−R	AIR−ANT1949
Description	Omnidirectional mast mount	Yagi mast or wall mount	Yagi mast mount
Application	Outdoor short-range point-to-multipoint applications	Indoor/outdoor directional antenna for use with access points or bridges	Outdoor midrange directional connections
Gain	5.2 dBi	10 dBi	13.5 dBi
Beam Width	360°H, 38°V	47°H, 55°V	30°H, 25°V
Polarization	Vertical	Vertical	Vertical

Table 4. Main Characteristics of the 2.4 GHz External Antennas (After Ref. 20.)

A Yagi antenna is a parasitic linear array, which is composed of parallel dipoles. However, the elements of the Yagi antennas that are used commercially for 802.11 services cannot be seen, because they are enclosed in a plastic shell so as to protect the antenna in the outdoor environments. Since these antennas are simple and offer relatively high gains, they have grown in popularity.

4. Performance Capabilities of the 1300 Series Bridge

Table 5 depicts the main performance capabilities of the 1300 series bridge, as they are presented by Cisco. At this point, it is necessary to note that the receive sensitivity is calculated with 3,200 byte packets and a Packet Error Rate (PER) of 10%, while the bridge role point-to-point range is achieved using a 21 dBi dish antenna at both the root

and the non-root bridge [19]. Cisco also notes that the referenced distances "are approximations and should be used for estimation purposes only." [19]

Available Transmit Power Settings	**802.11b:** 100 mW (20 dBm) 50 mW (17 dBm) 30 mW (15 dBm) 20 mW (13 dBm) 10 mW (10 dBm) 5 mW (7 dBm) 1 mW (0 dBm) **802.11g:** 30 mW (15 dBm) 20 mW (13 dBm) 10 mW (10 dBm) 5 mW (7 dBm) 1 mW (0 dBm)
Maximum Operational Receive Level	−20 dBm
Maximum Survivable Receive Level	10 dBm
Receive Sensitivity	1 Mbps: −94 dBm 2 Mbps: −91 dBm 5.5 Mbps: −89 dBm 11 Mbps: −85 dBm 6 Mbps: −90 dBm 9 Mbps: −89 dBm 12 Mbps: −86 dBm 18 Mbps: −84 dBm 24 Mbps: −81 dBm 36 Mbps: −77 dBm 48 Mbps: −73 dBm 54 Mbps: −72 dBm
Bridge Role Point−to−Point Range	Americas 4.5 miles (7 km) at 54 Mbps 14 miles (23 km) at 11 Mbps

Table 5. Performance Capabilities of the 1300 Series Bridge (After Ref. 19.)

5. Physical Specifications and Reliability of the 1300 Series Bridge

The physical specifications of the Cisco 1300 series bridge are such that they allow for the easy transfer and the quick installation of the unit in the case of outdoor applications in different environments. The Mean Time Between Failure (MTBF) rates characterize the reliability feature of the unit, which according to Cisco are 132,000 hours for the bridge interface and 400,000 hours for the power injector [19]. Table 6 summarizes the physical specifications of the bridge and the power injector.

	Bridge Interface	**Power Injector**
Dimensions	8 in. x 8.1 in. x 3.12 in. (20.3 cm x 20.57 cm x 7.87 cm)	4.62 in. x 4.76 in. x 1.07 in. (11.73 cm x 12.09 cm x 2.71 cm)
Weight	2.5 lb (1.25 kg)	2 lb (1 kg)
Operational Temperature	−22º to +131ºF (−30º to +55ºC)	−22º to +131ºF (−30º to +55ºC)
Operational Altitude	13,800 ft (4206 m)	13,800 ft (4206 m)
Humidity	0 to 100% at 100ºF (38ºC) (condensing)	0 to 90% at 100ºF (38ºC) (non−condensing)

Table 6. Physical Specifications of the 1300 Series Bridge (From Ref. 19.)

6. Portable AC Power Unit

Since the outdoor WLAN was implemented in remote locations and in different environmental sites, the need for a portable AC power unit was more than necessary. The rechargeable XPower Powerpack 400 Plus by Xantrex, shown in Figure 3, was used. This unit can deliver 400 Watts of portable AC power according to the manufacturer [21]. In practice, for the field measurements, two portable AC power units were needed, one in the bridge root location and the other in the bridge non-root location.

Figure 3. Portable AC Power Unit (From Ref. 21.)

7. Laptop Computers

The last of the equipment needed for the implementation of the outdoor WLAN were two laptops that were used in the root and non-root bridge locations, respectively. In fact, the Dell Latitude C840 laptop, which was used in the root bridge location, played the role of a wired network that would be extended with the designed WLAN. In the non-root bridge location, the second laptop, the Sony Vaio, represented another wired network or simply the extension of the first one. Table 7 presents the specifications of the two laptops that were used for the purposes of this research.

Characteristics	Laptop in the Root Bridge Location	Laptop in the Non Root Bridge Location
Type	Dell Latitude C840	Sony Vaio
Computer Processor	Intel Pentium 4	Intel Pentium 3
Operating System	Windows XP	Windows Me
RAM	768 MB	254 MB
Hard−disk	40 GB	20 GB
Display	UXGA 15", 1600 x 1200 pixels	15", 1400 x 1050 pixels

Table 7. Specifications of the Laptop Computers Used in the Implementation of the Outdoor WLAN

C. SELECTED EQUIPMENT FOR THE PERFORMANCE ANALYSIS OF THE 802.11G OUTDOOR WLAN

Since the required equipment for the implementation of the outdoor WLAN has been selected, the tools that were used in order to accomplish the performance analysis of the designed wireless network will now be presented. These tools include a GPS receiver, server software and the Cisco Aironet 1300 wireless bridge GUI.

1. eTrex Vista GPS Receiver

The eTrex by Garmin GPS receiver, shown in Figure 4, was used in this research to calculate the distance between the root and non-root bridge locations. According to [22] the accuracy of the GPS device varies from 3 to 15 m and therefore it can be used for purpose of this research with success.

Figure 4. Garmin GPS Receiver (From Ref. 22.)

2. Guildftpd FTP Server Software

This File Transfer Protocol (FTP) server software allows the transfer of data files between a server and a client and can be freely downloaded from the Internet. This FTP server software was primarily selected by Hsiung Wei Roy Chan because “it is easy to use, is highly recommended by other users and it is free.” [18] Based on this prior successful usage, the decision was made to install this software on the Dell laptop in the root bridge location and use it in order to enable file data transfers from the remote locations and determine the actual data throughput of the 802.11g wireless radio.

3. Cisco Aironet 1300 Wireless Bridge GUI

The GUI of the wireless bridge is a really useful tool because it can be used for various functions over the wireless interface. Basically, it can configure settings for the bridge radio such as the role in the radio network, data rates, power transmission, channel

settings, security options and others. It can also record summary and detailed statistics for the network 802.11g interface, such as received and transmitted packets, received signal strength in dBm, and much more information. Hence, the GUI provided the means of configuring the root and non-root bridges at each time under different settings and measuring the received signal strength at the remote locations as well as the Packet Error Rate (PER).

D. NETWORK ARCHITECTURE

Having chosen all the above equipment and tools for the implementation and performance analysis of the outdoor 802.11g WLAN, the wireless network architecture can now be presented. Figure 5 shows how the units were connected and how the designed wireless network diagram looked in both the root and non-root bridge locations.

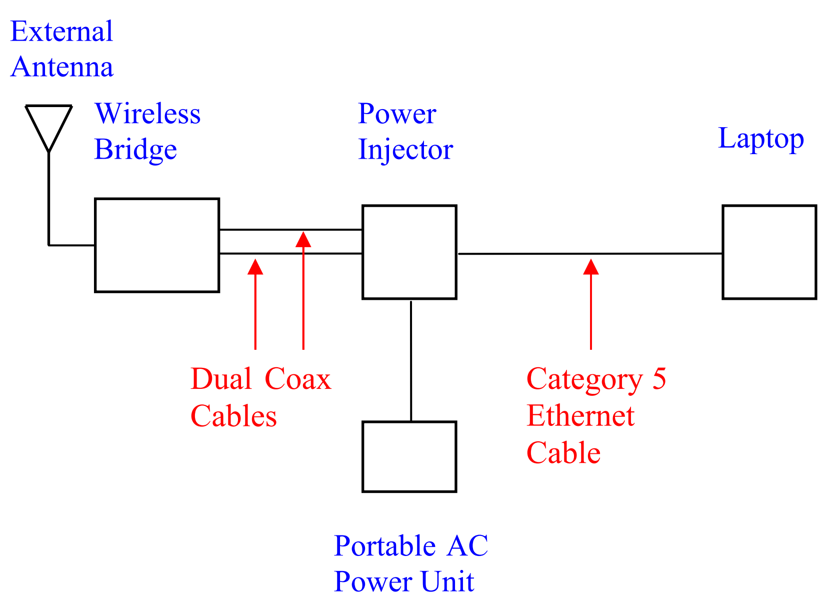

Figure 5. Wireless Network Diagram (After Ref. 19.)

E. RF ISSUES FOR THE 802.11: SMALL-SCALE FADING AND MULTIPATH

The term small-scale fading or simply fading refers to the rapid fluctuations of the amplitude, phase or multipath delay that a radio signal undergoes over a short period of

time or travel distance. These fluctuations occur due to changes in the transmission medium of the signal or changes in the paths that the radio signal follows with time. When two or more versions of a transmitted signal (multipath waves) arrive at the receiver at slightly different times they will interfere with each other and cause fading [2, 3].

Multipath in the radio channel can cause rapid changes in the received signal strength of a wireless client over short moving distances or even small time intervals. The presence of reflecting objects and scatterers in the channel generally has a negative influence in the signal energy, due to fluctuations in amplitude, phase, and time. The result is multiple versions of the transmitted signal with random amplitude and phases that arrive at the receiving antenna at slightly different times. These multipath components cause fluctuations in signal strength and therefore induce small-scale fading, signal distortion or both. The multipath components either add constructively or destructively at the receiver; in the second case, the signal level relative to noise declines and the signal detection at the receiver will be made more difficult. What's more, multipath propagation very often increases the time that the baseband portion of the signal needs to reach the receiver. This in turn can result in signal smearing due to intersymbol interference (ISI) [2, 3]. The effect of multipath interference is shown in Figure 6 for the case of indoor signal propagation.

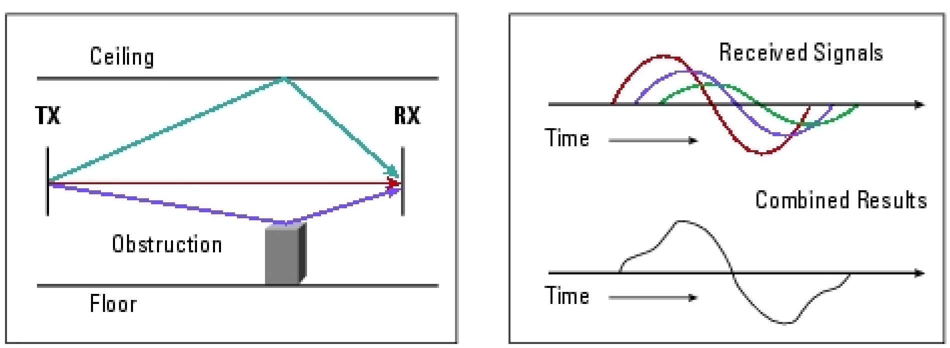

Figure 6. Multipath Interference (From Ref. 20.)

As an example, take the case of a wireless client in an urban area, which can be a small, medium or large city. In most cases, the antenna of the wireless client is well below the height of the antenna of an access point, a bridge, or even other surrounding structures, which means that there is not a Line of Sight (LOS) path between the transmitting and the receiving components. Even when there is a clear LOS path, multipath is also expected because of the reflections from the surrounding buildings and other moving objects. The received signal at the antenna of the wireless client will be the sum of many contributions that are coming from different locations. As mentioned above, these contributions have random phases, which means that their sum will vary widely. For example, it can obey a Rayleigh fading distribution. The result will be a distorted signal or a signal that is fading at the receiver end. It is also interesting to note that fading can occur in cases where the wireless client does not move, because of the movement of other surrounding objects (e.g., vehicles) in the radio channel [2].

Diversity techniques can be deployed to compensate for the errors and distortions that multipath fading introduces. These techniques are based on the fact that individual channels experience independent fading events. Hence, if several replicas of the same information signal transmitted over independently fading channels can be supplied to the receiver, then the probability that all the received components will fade simultaneously will be significantly reduced. One of the diversity techniques that is commonly used is the employment of multiple antennas at the receiver end. The restriction is that between two antennas there must be a separation of a few wavelengths so as to receive signals that fade independently [23]. The Cisco wireless bridge that was used for the implementation of the outdoor WLAN presented in this thesis offers the choice for antenna diversity, as was mentioned earlier in the presentation of the selected equipment.

F. SUMMARY

This chapter discussed some considerations that are related to the successful deployment of an outdoor 802.11 wireless LAN. Next, it presented the Cisco wireless equipment that was selected in order to implement the portable network infrastructure as well as the other tools that were necessary to measure the performance of the designed

outdoor WLAN. In the last section of the chapter, multipath propagation and small-scale fading were discussed as part of 802.11 radio frequency issues.

The next chapter will refer to the initial setup process of the root and non-root wireless bridges as well as the 802.11g radio settings of the two bridges that were configured.

IV. CONFIGURATION OF THE WIRELESS BRIDGES

The GUI of the Cisco wireless bridge was used for the initial configuration of the two bridges and for entering additional settings for a more detailed setup of the 802.11g WLAN. The bridge's web-browser interface also provided all the necessary information about the 802.11g radio interface and mainly the parameters of interest, such as received signal strength and PER.

A. INITIAL SETUP

The initial setup of the two bridges was done in an indoor environment using two omnidirectional 5.2 dBi external antennas. The Cisco Aironet 1300 Series Bridge Software and Hardware Guides were found to be extremely helpful for the whole process. After the bridges' IP addresses were assigned, the bridges' different web pages were browsed in order to configure the parameters of interest.

It is useful to note that when the two bridges are associated, which means that a WLAN has been established, both the GUIs (of the root and non-root bridge) can be controlled and accessed from one location, which in this case would be the remote location where the non-root bridge was located each time for the purposes of collecting the field measurements.

Next, the parameters that were chosen for the configuration of the two bridges will be briefly presented.

B. SETTINGS AND CONFIGURATION PROCESS

In Figure 7, screen capture of the Radio-802.11g Network Interface web page can be seen. As one can notice, from this page, the role of each bridge in the wireless radio network can be configured, as can the data rate that was chosen each time to use for data transmission. In the case being presented in this thesis, the first bridge was assigned the root role while the other bridge at the remote location sites was assigned the non-root role. The data ranges were constantly configured from the lowest value to the highest in order to measure the actual data throughput of the 802.11 WLAN at each selected location.

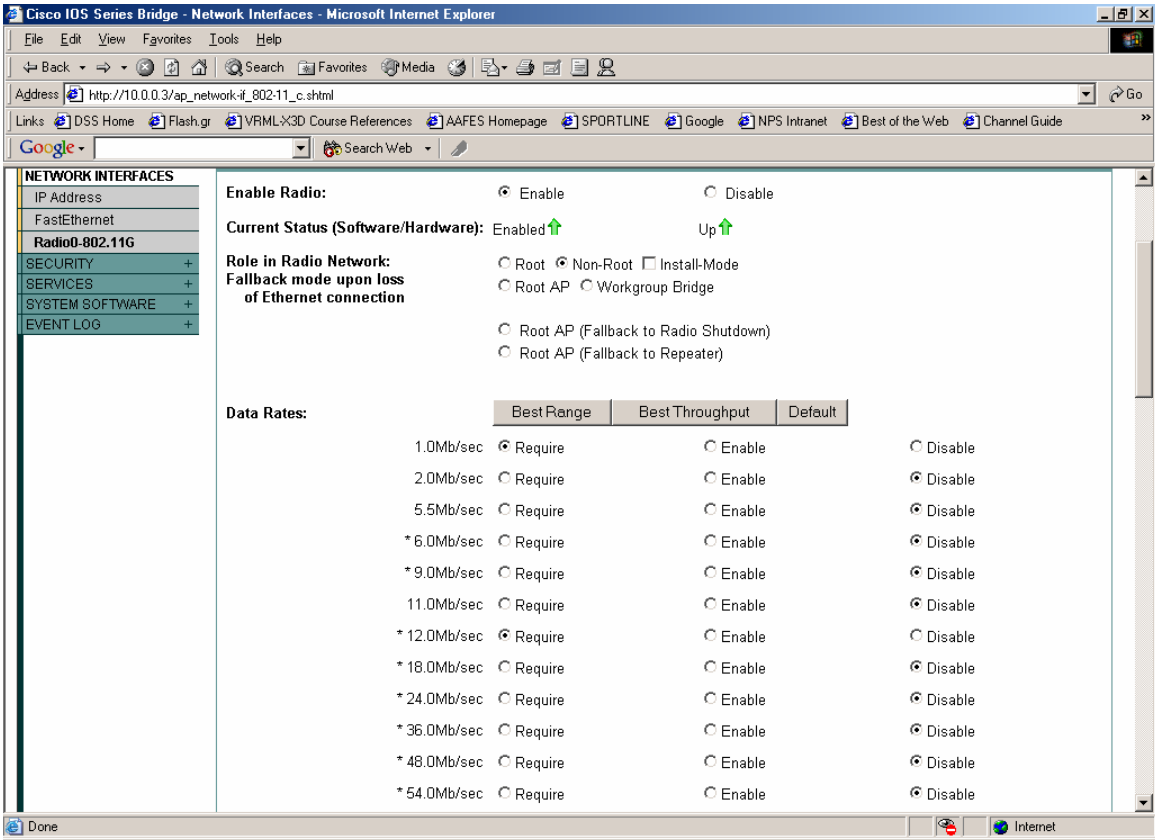

Figure 7. Configuring the Bridges' Role in Radio Network and Radio Data Rates

Apart from the above basic settings, the possibility for configuring other settings that are related to the 802.11g network interface was present, as can be seen in Figure 8. These additional options include:

- CCK Transmitter Power: The 802.11g radio transmits up to 100 mW for the 1, 2, 5.5 and 11 Mbps data rates. In the case being presented, the maximum setting (100 mW), which is allowed in the U.S. regulatory domain, was chosen.
- OFDM Transmitter Power: For the 6, 9, 12, 18, 24, 36, 48 and 54 Mbps data rates, the maximum transmit power for the 802.11g radio is 30 mW. Again, the maximum transmitter power (30 mW), which is allowed by the U.S. regulatory domain, was selected.
- Radio Channel: This setting remained at the default channel setting, which is least congested. This means that the bridge, at startup, scans for and selects the least congested channel.
- Radio Preamble: Short preambles were enabled by default and were kept for all the measurements since they improve throughput performance.

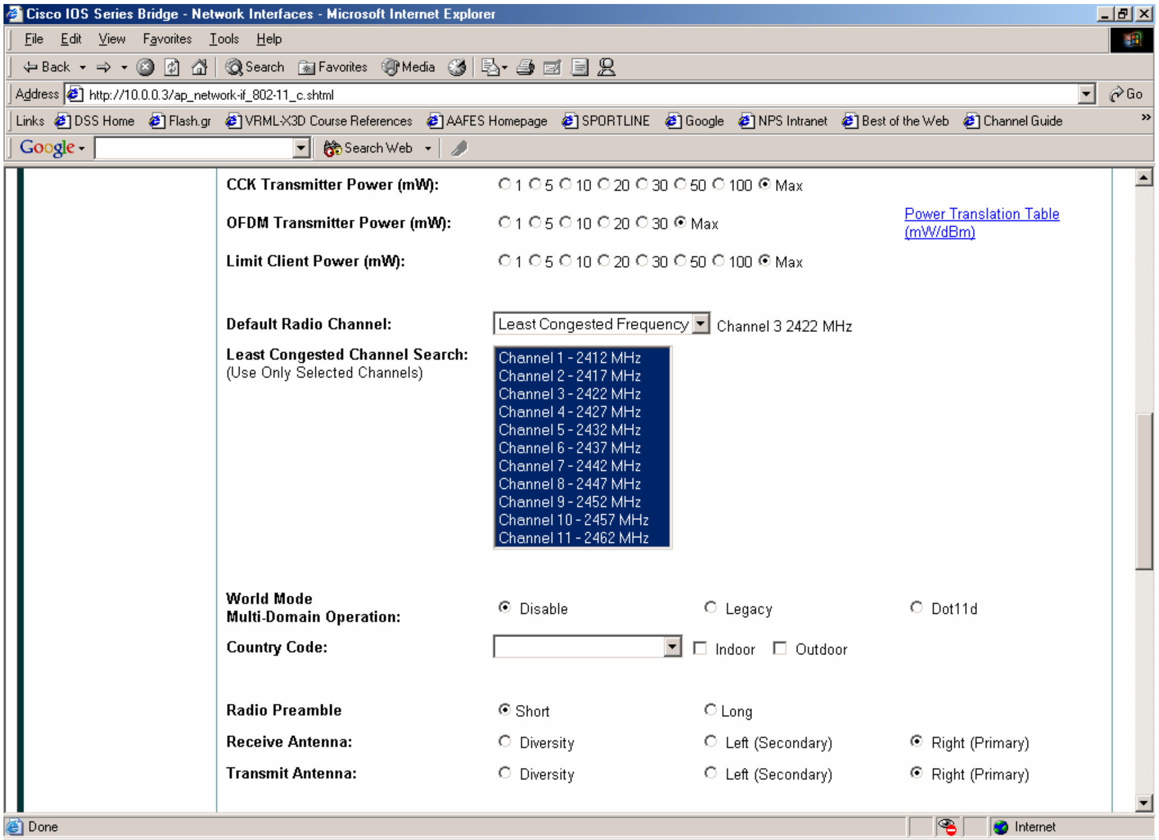

Figure 8. Configuring Bridges' Additional Parameters

Finally, Figure 9 shows the last settings that were chosen in order to configure the two bridges:

- Receive/Transmit Antenna: With this setting, the antenna each bridge uses to receive and transmit can be selected, since the unit supports diversity. For this research, only one external antenna at each bridge was used and the right connector on both bridges was arbitrarily chosen.
- Concatenation: This setting enables packet concatenation on the bridges radio. Using concatenation, the bridges combine multiple packets into one packet, and the result is reduced packet overhead and overall latency, and therefore increased transmission efficiency. The allowed values in this setting are from 1,600 bytes to 4,000 bytes. Both the minimum and the maximum value of bytes for were used for the measurements of this research, so as to make a comparison between these two values for the effective data throughput and the PER.
- Short Slot Time: By enabling short slot time (i.e., 9 microseconds), the throughput on the 802.11g radio is increased, since the overall back off time is decreased. The bridge uses this short slot time only when all clients associated to the 802.11g radio support short slot time. Hence, in this re-

search, this setting was enabled because the designed WLAN consisted of only two bridges only operating in the 802.11g mode.

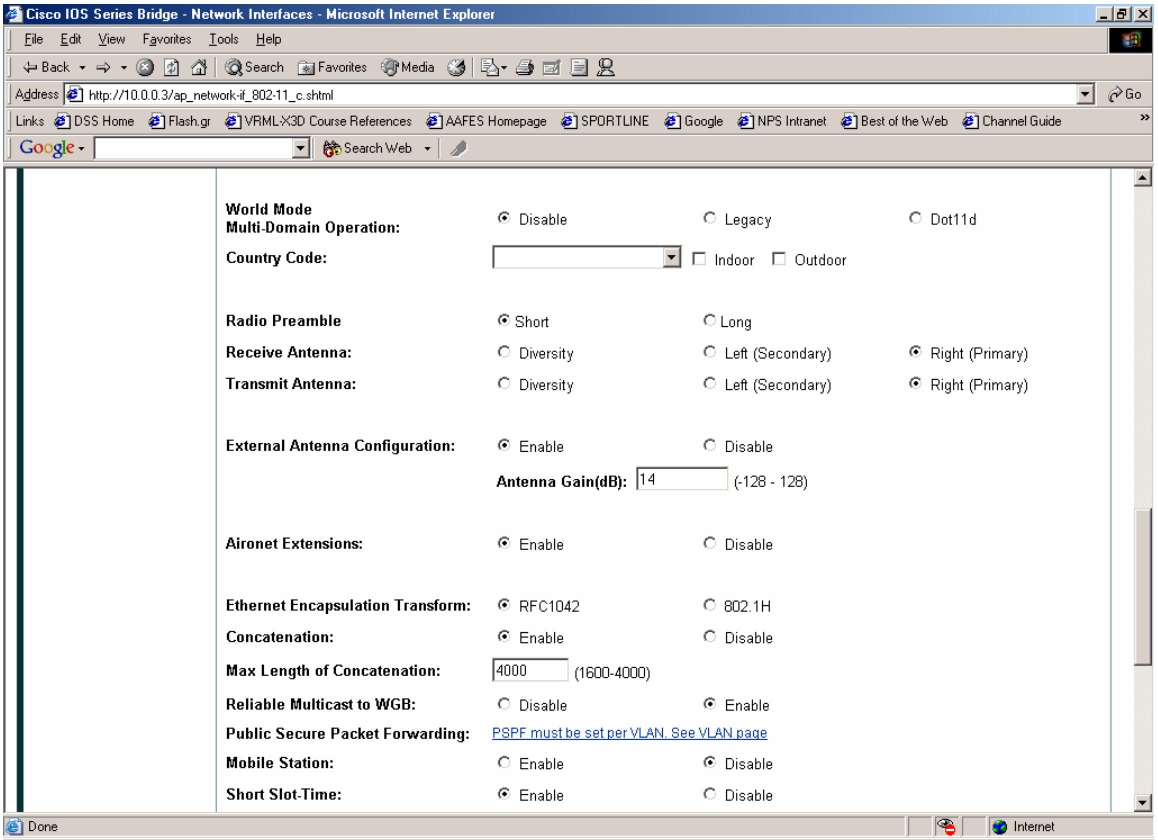

Figure 9. Configuring Bridges' External Antenna, Concatenation and Short Slot Time

Even more, in order to prevent unauthorized access and examine the effect of the security mechanisms to the performance of the designed 802.11g wireless LAN, the selection was made to conduct measurements using no security, WEP 40-bit security and WEP 128-bit security. The appropriate configurations were made each time using the Express Security web page of the bridges.

C. SUMMARY

This chapter presented, in brief, the setup and configuration process of the two wireless 802.11g bridges with the use of the GUI.

The next chapter is of great importance because it refers to the actual implementation of the 802.11 outdoor WLAN and presents and analyzes the experimental field measurements under the following three different operational environments:

- Suburban area (small-sized city) with LOS
- Medium density vegetation with non-LOS
- Coastal environment with LOS

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V. IMPLEMENTATION OF THE 802.11G OUTDOOR WLAN− FIELD MEASUREMENTS AND RESULTS

This chapter will present the implementation of the designed outdoor 802.11g WLAN under three different environments in order to examine how the results from the field measurements differ in each environment. In each case, the received signal strength, actual data throughput and packet error rate were recorded and then analyzed to assess the performance of the 802.11g WLAN in these three operational scenarios.

A. GENERAL DESCRIPTION

The three different operational outdoor environments that were used to conduct field measurements were the following:

- Suburban area, small-sized city: this case is approximately represented by the city of Monterey. The measurements that were taken in this environment were done with LOS.
- Medium density vegetation: the measurements for this case were conducted at a site in Fort Ord with non-LOS.
- Coastal environment: for this scenario, measurements were conducted using the Commercial Fisherman's Wharf as the location of the root bridge and the coast of Monterey Bay as the location of the non-root bridge, in order to succeed with as much water body as possible. These measurements were also done with LOS.

More details about the selection of the points that the field measurements took place, as well as a visual image of each environmental scenario, will be given in the next sections of this chapter.

The two bridges and the external antennas were mounted on two masts respectively at a height of approximately two meters. Depending on the environmental scenario, the masts were placed at different locations, meaning that the effective height of the root mast was sometimes higher and yet other times lower than this of the non-root mast. Since the antennas were directional they had to be installed and positioned properly, or in other words, they had to be aligned for maximum received signal strength. This was achieved each time, after the association of the two bridges had occurred, using the LED indications of the bridge unit. According to [24], the antenna had to be adjusted until as

many LEDs as possible were on and the rest were blinking as fast as possible. With all three LEDs on, the signal was good enough to support the maximum data rate.

When the alignment procedure had been completed, the measurement process could start by transferring a large data file from the root bridge to the non-root bridge at the different data rates that 802.11g supports. In order to record the results, the GUI of the non-root bridge and the FTP server was used.

B. SUBURBAN AREA (SMALL-SIZED CITY) MEASUREMENTS

This section of the chapter will provide the reader with the results of the field measurements at different outdoor locations in the suburban area of Monterey.

1. Selecting the Points of Field Measurements

In order to find appropriate locations for conducting the field measurements in the urban area, a preliminary plan was used. This plan was based on the fact that the field non-root bridge locations should provide a clear LOS with the location of the root bridge and of course, the reverse. The roof of Spanagel Hall was the choice for mounting the root bridge mast and selecting the field measurement points, since it provides a very clear view of the city of Monterey. Initially the possible locations from the Spanagel roof were checked and then it was verified that these locations could be, in fact, be used, meaning that they would be accessible by a car and provide a satisfactory clearance. Finally, six locations were selected for setting the non-root bridge mast each time, with range and elevation data as shown in Table 8.

Measurement Points	Distance from Root Bridge (m)	Elevation (m)
Spanagel Roof	0	41
1: Ocean Ave. & Eighth St.	400	18
2: Monterey Peninsula College	1000	35
3: Commercial Fisherman’s Wharf	1600	3
4: Van Buren St. & Seeno St.	2000	20
5: W. Franklin St.	2400	30
6: W. Franklin St. − Presidio Gate	3100	98

Table 8. Range and Elevation Data of the Selected Suburban Area Test Points

The Garmin GPS receiver provided the range and elevation data for each location listed in Table 8. The elevation was measured from the mean sea level. It was noticed that the effective heights of the root and non-root bridge masts differed in each location. This meant that in each field test point the external antennas had to be positioned carefully in order to obtain the strongest received signal strength and therefore the best throughput performance.

For all the measurements in this operational scenario, two 13.5 dBi Yagi outdoor midrange antennas were used as external antennas, since they approximately matched the range requirements and could be easily installed at each test location

2. Results at Test Point 1

At the first measurement point it was decided to conduct measurements using two different sized zipped files for transfer, one of approximately 22 Mbytes and another one of approximately 88 Mbytes. This was done so to determine whether file size has an impact on the effective data throughput and on the PER, and moreover, to decide which file would be used for the next measurements.

a. Using the 22 Mbytes File

The measurements were carried out using the file of 22 Mbytes under four different settings: no security with concatenation 1600 (i.e., the packet length is 1600 bytes), WEP 40-bit with the same concatenation, WEP 128-bit with the same concatenation, and finally, no security with concatenation 4000 (i.e., the packet length is 4000 bytes). The results for the effective data throughput are shown in Table 9.

Data Link Rate (Mbps)	Actual Throughput (Mbps)			
	Conc. 1600 No WEP	Conc. 1600 WEP 40-bit	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
1	0.76	0.74	0.76	0.77
2	1.45	1.47	1.48	1.47
5.5	3.44	3.64	3.59	3.86
6	4.44	4.26	4.09	4.45
9	5.3	5.5	5.33	6.33
11	6.54	6.5	6.44	6.84
12	8.01	8.05	7.91	8.28
18	10.83	10.82	11.12	12.03
24	13.43	12.45	13.05	14.51
36	16.77	16.85	16.77	17.88
48	19.28	19.28	19.62	20.89
54	19.97	19.62	19.62	23.61

Table 9. Throughput Results at 400 m Using 22 Mbytes File

The results of Table 9 have been depicted in Figure 10.

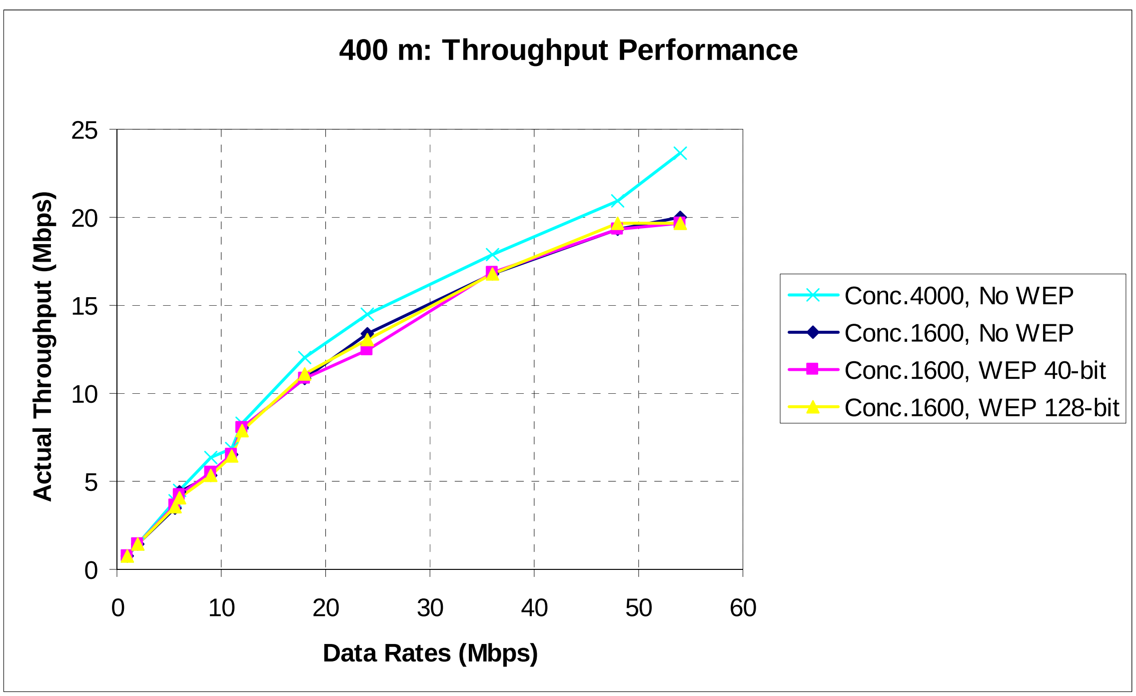

Figure 10. Throughput Performance at 400 m Using 22 Mbytes File

Looking both at Table 9 and Figure 10, it can be seen that the throughput performance for the cases where concatenation 1600 and no WEP, WEP 40-bit and WEP 128-bit were used as security mechanisms did not change significantly. This could mean that the use of the WEP security mechanism did not generally affect the actual throughput results at this test point. On the other hand, the derived results using concatenation 4000 were higher, especially at the rates above 18 Mbps. What is also interesting to note is the fact that for the data rates that use DSSS (1, 2, 5.5 and 11 Mbps), as well as the low and medium OFDM data rates (6, 9, 12, 18 and 24 Mbps), the actual throughput results were more than 60% close to the theoretical data rates. However, the high OFDM data rates of 36, 48 and 54 Mbps presented a reduction in their throughput performance more than 50%. Of course, the results in all test points will be more useful for generalizing the above observations.

As far as the PER is concerned, for all the measurements it was referred to as the number of packets whose data was invalid at reception (Cyclic Redundancy Check errors) as they were recorded from the GUI of the non-root bridge. The average PER measured values for the four cases were the following:

- Concatenation 1600, No WEP: 2.59%
- Concatenation 1600, WEP 40-bit: 2.88%
- Concatenation 1600, WEP 128-bit: 2.40%
- Concatenation 4000, No WEP: 1.80%

Another useful tidbit is that the use of concatenation 4000 resulted in a reduced PER which agrees with the higher throughput performance that was seen earlier. For the other three cases, the PER was maintained at almost the same level, with the WEP settings showing a slightly better performance.

The last thing that was measured at this test point was the received signal strength. In the previous chapter small scale fading and multipath was discussed and the fact that fading can also occur even when the wireless client does not move, because of the movement of other surrounding objects in the radio channel, was emphasized. This exact phenomenon was observed during the collection of the field data of the received signal strength. Although the location remained stationary, the results for the received

signal strength at different time intervals showed minor changes. These amplitude variations in the received signal were due to the time-variant multipath characteristics of the radio channel.

Table 10 contains the measured values of the received signal strength at this specific test location that was used and was 400 m away from the location of the root bridge. These values were recorded at each data rate a few seconds after the file transfer had begun, while the time between the transitions from one data link rate to another was absolutely random. At this point, it should be noted that the CCK power was configured at a higher value than the OFDM power (100 mW and 30 mW respectively). As a result, the received signal strength for the DSSS data rates (1, 2, 5.5, 11 Mbps) was different than the one for the OFDM data rates.

Data Link Rate (Mbps)	Received Signal Strength (dBm)			
	Conc. 1600 No WEP	Conc. 1600 WEP 40-bit	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
1	−45	−45	−46	−46
2	−45	−45	−47	−47
5.5	−45	−46	−47	−46
6	−51	−51	−52	−52
9	−51	−51	−52	−52
11	−45	−45	−46	−46
12	−51	−51	−51	−52
18	−51	−52	−51	−52
24	−51	−51	−51	−52
36	−51	−52	−52	−52
48	−51	−51	−52	−52
54	−50	−52	−52	−52

Table 10. Received Signal Strength at 400 m

Note that the best achievable value was −45 dBm for the DSSS data rates while the worst was −52 dBm for the OFDM data rates.

b. *Using the 88 Mbytes File*

The same exact measurements were repeated with a zipped file size of approximately 88 Mbytes. The results for the data throughput are tabulated in Table 11 and graphically presented in Figure 11.

Data Link Rate (Mbps)	Actual Throughput (Mbps)			
	Conc. 1600 No WEP	Conc. 1600 WEP 40-bit	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
1	0.75	0.75	0.78	0.77
2	1.49	1.48	1.52	1.51
5.5	3.53	3.58	3.63	3.87
6	4.09	4.08	4.3	4.22
9	5.55	5.74	5.91	5.96
11	6.39	6.36	6.17	7.1
12	6.92	7.27	7.16	7.52
18	10.21	9.78	9.52	9.85
24	12.17	13.12	12.88	14.59
36	16.47	16	16.47	19.75
48	20.1	17.62	19.37	21.74
54	20.23	19.58	19.62	24.56

Table 11. Throughput Results at 400 m Using 88 Mbytes File

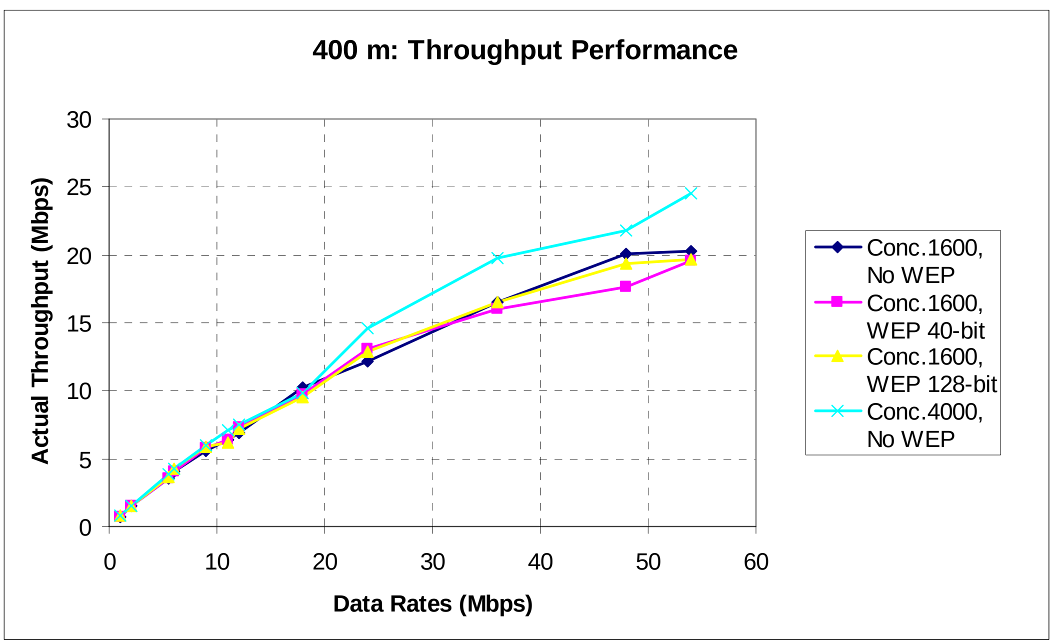

Figure 11. Throughput Performance at 400 m Using 88 Mbytes File

What can easily be observed from the results is that the bigger file size did not affect the actual throughput performance, since the results are in the same range as before. It is also noticeable that concatenation 4000 again showed a higher performance for data rates greater than 18 Mbps, while the other three settings were fairly close in their performance, with WEP 40 resulting in a slightly worse throughput performance. The maximum data throughput that was achieved was 24.56 Mbps and was approximately 1 Mbps higher than the one achieved with the 22 Mbytes file. This observation simply shows the multipath effects that each time influence the results.

On the other hand, the PER for this case increased significantly. The average PER results for each setting were:

- Concatenation 1600, No WEP: 5.59%
- Concatenation 1600, WEP 40-bit: 6.88%
- Concatenation 1600, WEP 128-bit: 5.40%
- Concatenation 4000, No WEP: 5.21%

Hence, it is concluded that the PER performance of the designed wireless system depended on the size of the file that was used for conducting the measurements, which means that using the bigger file size ended up in an increased PER. Of course it would be more reliable to execute further measurements in order to generalize this suggestion, but the amount of time that was required for the 88 Mbytes file transfer, especially at the low data rates, was rather excessive. Therefore the decision was made to continue the measurements in all test points using the smaller file size of 22 Mbytes, which had resulted in a more effective PER performance. As far as the received signal strength is concerned, the same comments apply as before.

3. Results at Test Point 2

The second test location point that was used for field measurements was 1000 m away from the root bridge location. It was decided to once again conduct measurements with the four configurations that were tried earlier in order to get a clearer picture of the derived throughput and PER results. Table 12 contains the results for this test point.

Data Link Rate (Mbps)	Actual Throughput (Mbps)			
	Conc. 1600 No WEP	Conc. 1600 WEP 40-bit	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
1	0.75	0.75	0.74	0.73
2	1.46	1.42	1.39	1.4
5.5	3.33	3.35	3.45	3.39
6	3.73	4.22	3.98	4.19
9	5.07	5.2	5.82	6.2
11	6.19	6.26	6.18	6.66
12	7.65	6.69	7.58	7.31
18	10.15	9.07	9.27	11.12
24	11.73	10.89	12.45	13.48
36	12.31	11.85	15.34	17.41
48	15.87	16.43	17.78	19.73
54	17.22	18.29	18.06	21.29

Table 12. Throughput Results at 1000 m

The results indicate a small reduction at the effective throughput, especially for data rates greater than 24 Mbps, when compared with the results at 400 m. It is important to notice that for these data rates, both concatenation 1600 without WEP and with WEP 40-bit performed inferior to the other two settings. A reasonable explanation about this could be that the test location at the Monterey Peninsula College suffers from greater multipath effects. Therefore, the throughput performance of the four different settings that were chosen was pretty close in all three cases when using concatenation 1600, while the use of concatenation 4000 seemed to improve performance. It should also be mentioned that the use of the WEP mechanism did not significantly affect the throughput performance, which resulted in minor fluctuations that depended on the test location and the ever-changing environmental conditions.

Figure 12 illustrates the results at this test point and shows the fall in the throughput for concatenation 1600 with no WEP and with WEP 40-bit.

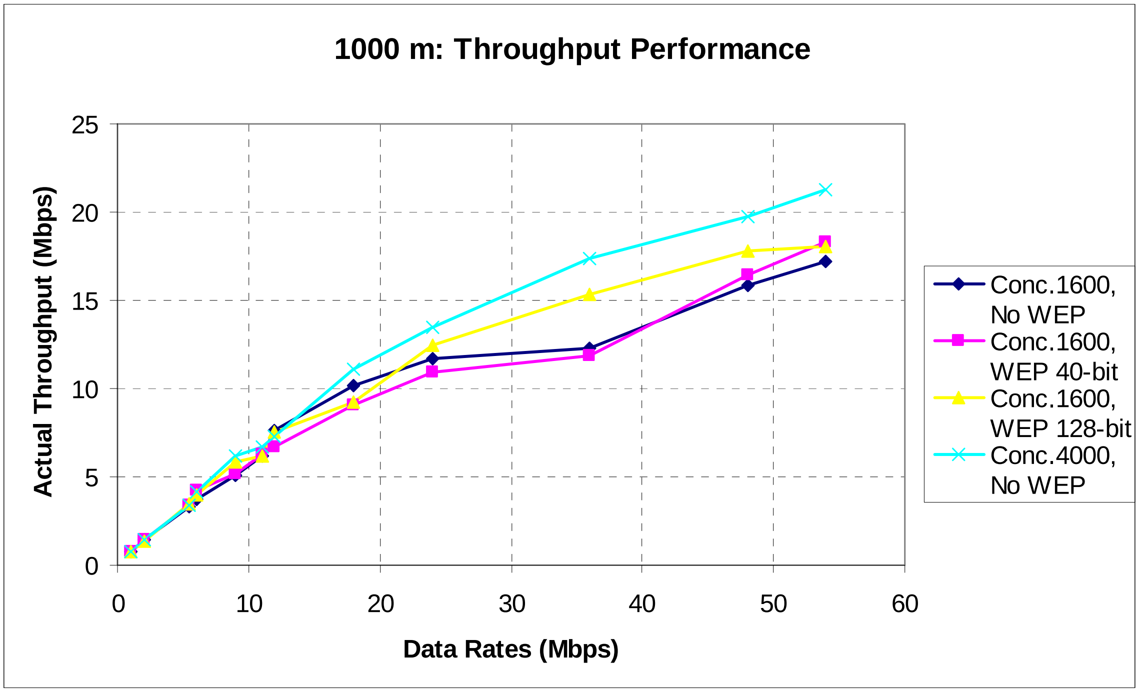

Figure 12. Throughput Performance at 1000 m

Since the last two settings had performed better than the first two, it was reasonable to obtain the following values for the average PER:

- Concatenation 1600, no WEP: 3.37%
- Concatenation 1600, WEP 40-bit: 3.68%
- Concatenation 1600, WEP 128-bit: 2.94%
- Concatenation 4000, no WEP: 2.63%

Having all the above data in mind, it was determined that for the next measurements of this research, the two configurations that had resulted in the best throughput and PER performance at the first two field test points would be used. It was seen that concatenation 1600 with WEP 128-bit and concatenation 4000 without WEP achieved the best values in actual data throughput and PER at the selected test points. Of course, this could also be due to the time-variant multipath characteristics of the radio channel at the moments that these measurements were conducted.

Regarding the received signal strength, the maximum value was −56 dBm for the DSSS data rates, while the worst was −64 dBm for the OFDM data rates.

4. Overall Actual Data Throughput Performance

The data collected for the real throughput performance at the different field test points of this operational scheme can be summarized in Table 13. These results have been obtained using the 22 Mbytes transfer file and the two most effective settings that were discussed before. Note that NA means that association between the two bridges could not be established while TA means that the file transfer aborted although there was association between the bridges.

Distance (m)	Setting	Actual Data Throughput (Mbps) in the 802.11g Data Rates (Mbps)											
		1	2	5.5	6	9	11	12	18	24	36	48	54
400	Conc.1600 WEP 128-bit	0.76	1.48	3.59	4.09	5.33	6.44	7.91	11.12	13.05	16.77	19.62	19.62
	Conc.4000 No WEP	0.77	1.47	3.86	4.45	6.33	6.84	8.28	12.03	14.51	17.88	20.89	23.61
1000	Conc.1600 WEP 128-bit	0.74	1.39	3.45	3.98	5.82	6.18	7.58	9.27	12.45	15.34	17.78	18.06
	Conc.4000 No WEP	0.73	1.40	3.39	4.19	6.20	6.66	7.31	11.12	13.48	17.41	19.73	21.29
1600	Conc.1600 WEP 128-bit	0.70	1.39	3.25	3.48	5.16	5.66	6.84	8.63	9.84	13.10	11.81	12.12
	Conc.4000 No WEP	0.72	1.42	3.39	3.48	4.90	6.45	6.74	8.91	11.9	14.01	14.58	11.99
2000	Conc.1600 WEP 128-bit	0.74	1.41	3.23	3.69	5.22	5.53	6.14	8.75	9.78	NA	NA	NA
	Conc.4000 No WEP	0.76	1.49	3.61	3.77	5.46	6.60	7.30	9.66	11.08	NA	NA	NA
2400	Conc.1600 WEP 128-bit	0.64	1.13	3.36	3.72	4.99	5.54	6.28	6.35	5.59	NA	NA	NA
	Conc.4000 No WEP	0.73	1.41	3.44	3.48	4.45	5.84	6.46	6.5	5.68	NA	NA	NA
3100	Conc.1600 WEP 128-bit	0.72	1.46	3.54	3.71	5.35	5.90	TA	NA	NA	NA	NA	NA
	Conc.4000 No WEP	0.77	1.54	3.62	4.2	5.60	6.27	TA	NA	NA	NA	NA	NA

Table 13. Data Throughput Results for All Test Points in the Urban Area

The data in Table 13 is graphically shown in Figures 13 and 14. It is obvious that the best value of effective data throughput was achieved at the closest test point to the root bridge using concatenation 4000 with no WEP mechanism.

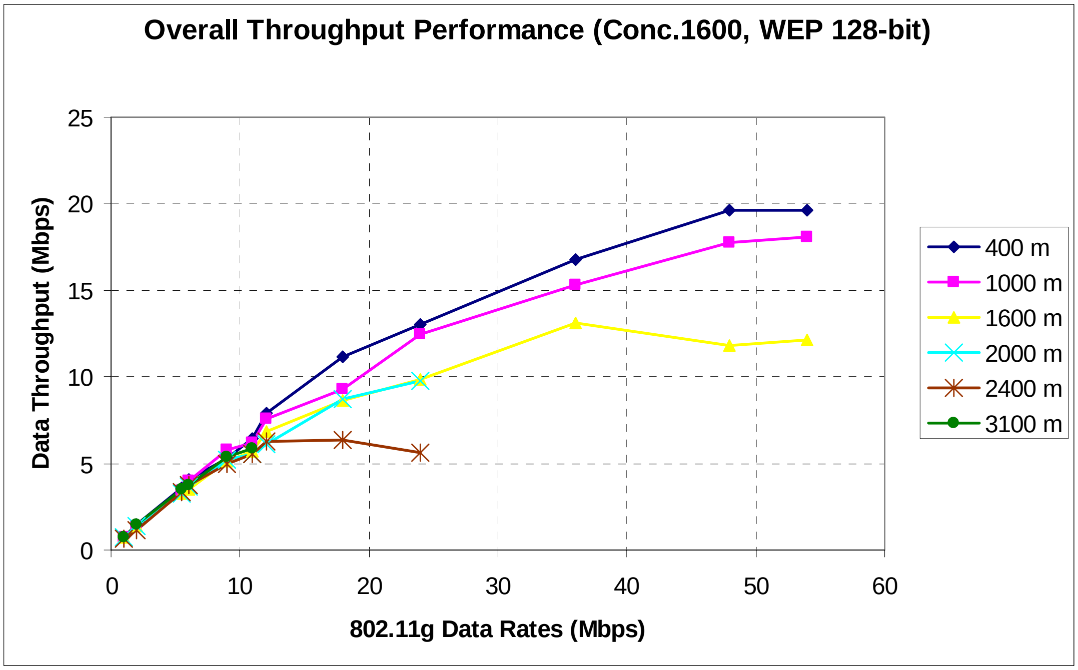

Figure 13. Overall Throughput Performance at Suburban Area Using Conc. 1600 and WEP 128-bit

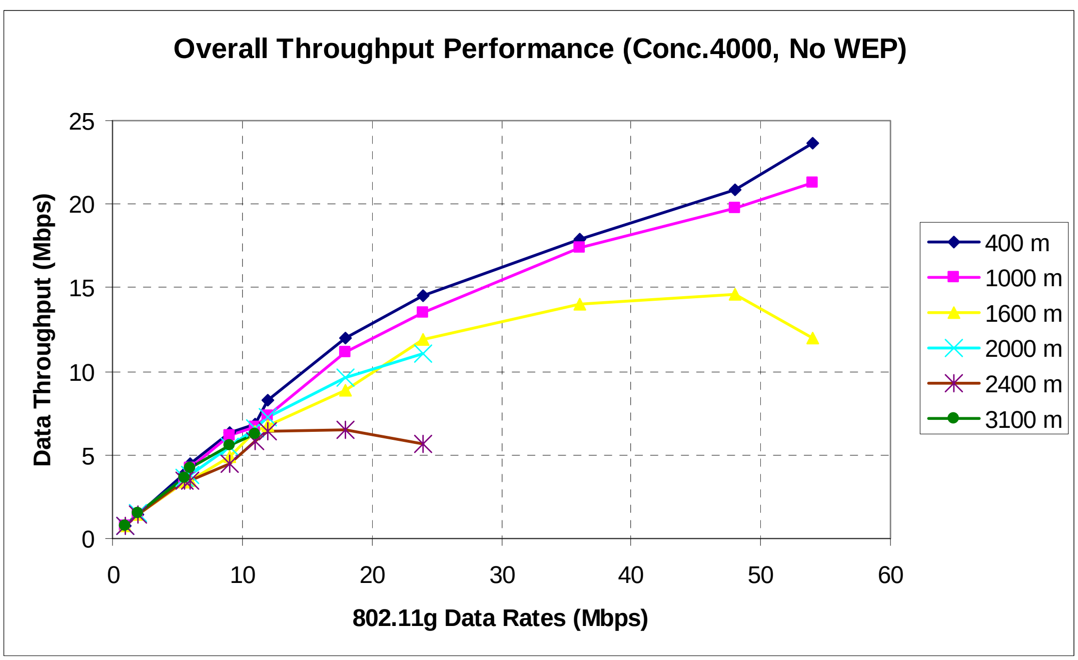

Figure 14. Overall Throughput Performance at Suburban Area Using Conc. 4000

Now that all the data has been presented, some remarks can be made on the derived results. First of all, the actual throughput results for the data rates from 1 Mbps to 12 Mbps for all the test points did not drop below 50 % of the corresponding theoretical data values. In fact, although the distance was increased, the results for these data rates did not degrade considerably but showed an insignificant reduction. Even at the distance of 3,100 m, the achieved data throughput for the data rates from 1 Mbps to 11 Mbps remained above 50% of these theoretical values.

On the other hand, the data throughput for the 802.11g rates from 18 Mbps to 54 Mbps decreased significantly as the distance increased. At the distance of 1,600 m, the maximum value that was achieved was 14.58 Mbps at the theoretical 48 Mbps, which represents approximately a 30% actual throughput at this data rate. At the highest 802.11g data rate of 54 Mbps, the best achievable value was 12.12 Mbps, perhaps due to multipath effects, which is less than 25% of this theoretical data rate. Note also that association between the bridges for data rates greater than 24 Mbps could not be established at the distance of 2,000 m. At 3,100 m, the file transfer at the data rate of 12 Mbps could not be completed, while for the rest of the data rates, steady and reliable association could not be established.

Of course, it should be kept in mind that all these measurements were conducted using the 13.5 dBi Yagi outdoor midrange antennas. According to Cisco, the approximate range at 54 Mbps for this antenna is 2.27 km, under ideal outdoor conditions. Since the WLAN was deployed at a multipath environment, the derived results were absolutely normal and indicated that the designed WLAN could operate successfully even at distances of 3.1 km with maximum actual throughput of around 6 Mbps.

Another observation has to do with the modulating schemes that 802.11g uses. From the above discussion it is clear that BPSK, QPSK, and CCK that are used with DSSS for the 1, 2, 5.5 and 11 Mbps (the 802.11b data rates) perform quite satisfactorily. In this research, with the specific equipment that was used and the test location points that were selected, they always resulted in an actual throughput performance approximately in the order of 50−75% of the theoretical data rates.

For the modulation schemes that use OFDM, the situation is a little more different. For the 6, 9, 12 and 18 Mbps that BPSK and QPSK used, the results proved that the data throughput ranged from as low as 35% to 70% depending on the location. However, the results for the higher data rates that use 16 and 64 QAM were notably lower. At 24 and 36 Mbps, the achieved throughput was 25−60%, while at 48 and 54 Mbps it approached 23−43%. Even at 400 m, the best throughput result was 23.61 Mbps, which is approximately 44% of the theoretical 54 Mbps. All these observations simply show that the QAM modulation scheme, although it can provide high data throughput values, is generally more sensitive to noise and multipath effects than the other 802.11g modulating schemes. This is why when the distance increases, 802.11g cannot support the higher data rates as effectively as the lower ones.

The last observation of the above results is related to the two different settings that had been selected for the configuration of the bridges. As it had been noticed earlier, concatenation 4000 without WEP showed a better throughput performance than concatenation 1600 with WEP 128-bits most of the time.

5. Overall Packet Error Rate Performance

The PER results for the six field test points in the city of Monterey are presented in Table 14. These values represent the average PER that was achieved at each location and is not related to the number of times a packet or RTS had to be retried.

Distance (m)	Average PER (%)	
	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
400	2.40	1.80
1000	2.94	2.63
1600	4.78	4.23
2000	5.67	5.15
2400	9.73	9.09
3100	8.14	7.65

Table 14. PER Results for the Suburban Area

The first remark about the results concerns the two selected settings. Concatenation 4000 with no WEP security ended up in a smaller PER than that of concatenation

1600 with WEP 128-bit security mechanism. This result was somewhat expected since the throughput performance of the first setting was found to be a little more effective. The second comment is that the average PER increased as the distance between the two bridges increased, which was also predictable since the data throughput decreased.

Figure 15 depicts the derived values for the PER at the different distances. Notice that the test point at 3,100 m resulted in a lower PER than the corresponding test point at 2,400 m. This probably happened because the selected test point at 2,400 m was at a street location with a great deal of traffic from running cars, which might have caused the multipath components to add destructively, and therefore affected the throughput and PER performance.

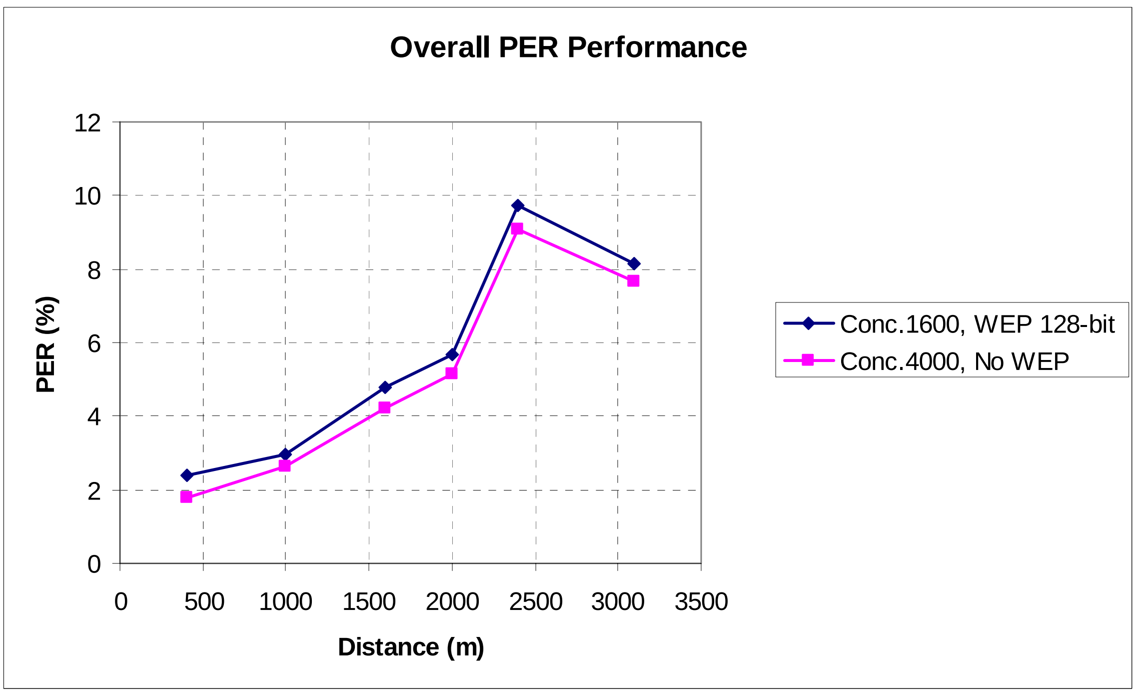

Figure 15. PER Performance for the Suburban Area

6. Overall Received Signal Strength Performance

The results that were presented in Table 10 for the received signal strength at the nearest field point indicate the effect of small-scale fading. Actually, since the 802.11g outdoor WLAN was implemented in a multipath environment, it was expected that this

effect would take place at the different selected field test points, depending on the locations themselves, the surrounding clearance and the multipath characteristics of the channel.

Figures 16 and 17 illustrate small-scale fading at two test points. The illustrated values in Figure 16 were taken at 1,600 m when the data link rate was 54 Mbps, while the values in Figure 17 were recorded at 3,100 m with a data rate of 9 Mbps. In both cases, the time interval between the measurements was approximately 5 seconds.

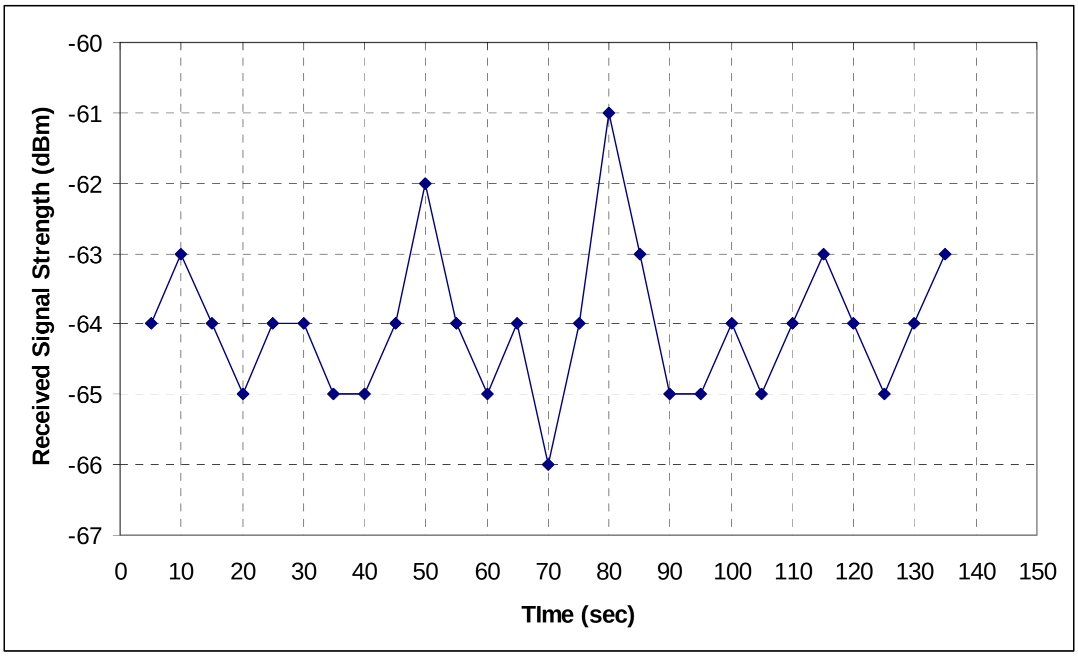

Figure 16. Small-Scale Fading at 1,600 m and 54 Mbps

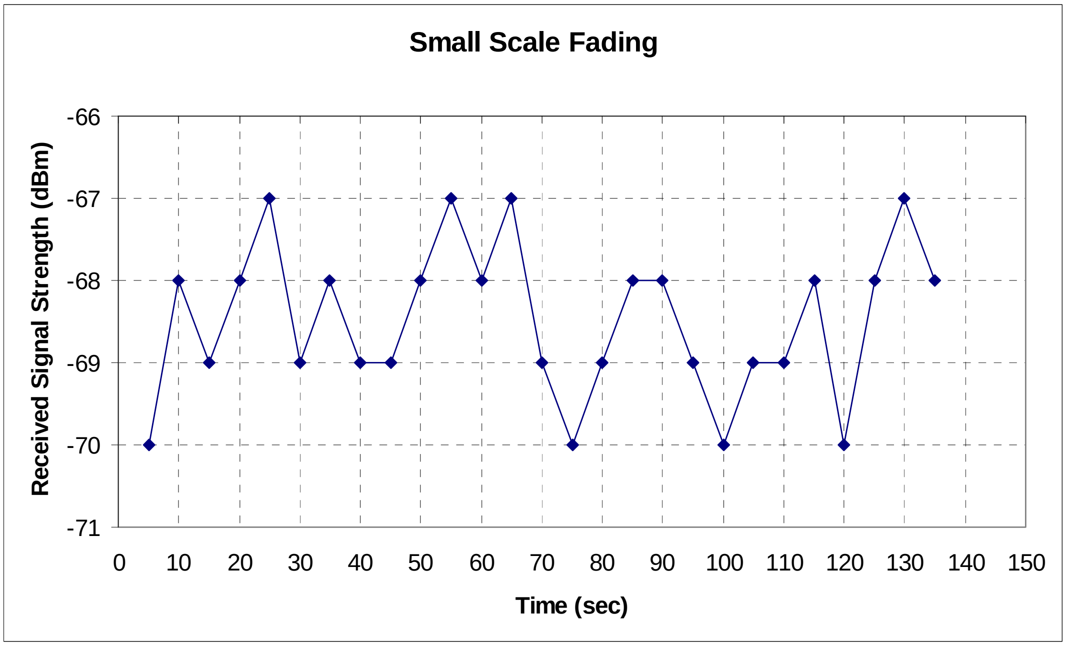

Figure 17. Small-Scale Fading at 3,100 m and 9 Mbps

The measurements for the received signal strength were taken at each location at absolutely random time intervals using the non-root GUI. Table 15 tabulates three different results for each of the six test points in both the DSSS and the OFDM data rates. The first and second result are the worst and the best values that were observed during the time that the data field collection took place, while the third is the average received signal strength that was calculated from at least 50 arbitrary measured values, so as to provide a more reliable and representative outcome. The minimum and maximum values of the received signal strength again indicate that the results were continually affected by the multipath characteristics of the channel.

Distance (m)	Received Signal Strength (dBm)					
	DSSS Data Rates			OFDM Data Rates		
	Min	Max	Average	Min	Max	Average
400	−47	−45	−45.69	−52	−50	−51.43
1000	−59	−56	−57.28	−64	−60	−61.56
1600	−61	−60	−60.60	−66	−61	−65.32
2000	−62	−61	−61.73	−68	−66	−66.95
2400	−67	−62	−64.41	−73	−69	−70.29
3100	−64	−61	−62.05	−70	−67	−68.36

Table 15. Received Signal Strength Results for the Suburban Area

A more useful representation of the above results is shown at Figure 18. It is clear that the average received signal strength for both rates decreased as the distance between the two bridges increased in range from 400 to 2,400 m. At 3,100 m, the result was better than it was at 2,400 m. At the test point of 2,400 m, which was on a busy street as was mentioned earlier (which also caused difficulty during the alignment of the external antennas of the bridges), the multipath components probably added destructively and therefore acted against the received signal strength. On the other hand, the last test point at the distance of 3,100 m was situated higher than the Spanagel roof (i.e., root bridge) and in a more open site, and as a result, the multipath components acted in favor of the received signal strength. All this discussion agrees with the previous results for the data throughput and the PER at the different locations.

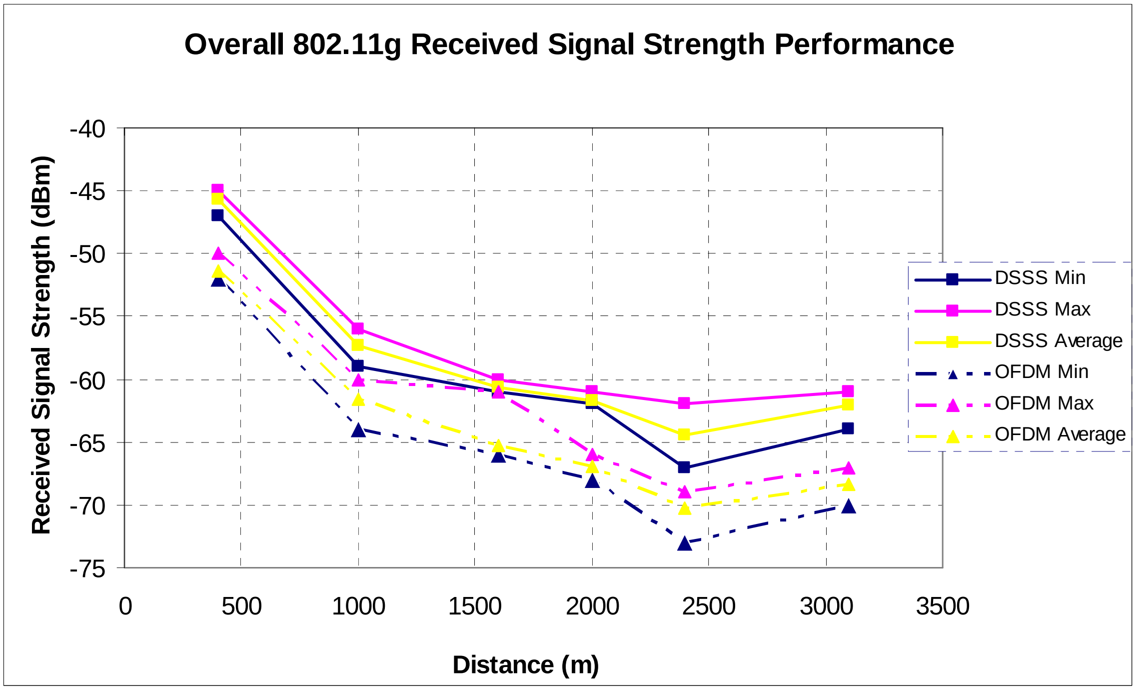

Figure 18. Received Signal Strength Performance for the Suburban Area

In the next chapter, more comments about the received signal strength at each distance will be made, since there will be a comparison between the measured values and the theoretical results that come from the prediction models.

7. Summary of the Results in the Suburban Area (City of Monterey)

The measured results at the first two field test points indicated that the use of the WEP mechanism did not, in general, negatively affect the throughput and the PER performance. On the other hand, the use of concatenation 4000 resulted in an improved performance in almost all cases. Concatenation 1600 with WEP 128-bit and Concatenation 4000 without WEP were selected for the conduction of all the measurements since, in absolute numbers, they performed better.

Table 16 summarizes the results for the data throughput in the different 802.11g data link rates. These results were obtained using the collected measurements from all the test points in the urban area of the city of Monterey. It is noticeable that the setting with concatenation 1600 and WEP 128-bit ended up with a somewhat worse average throughput performance than concatenation 4000 without the WEP security. Note also that above

18 Mbps, the actual average throughput results deviated between 50 and 70 % from the corresponding theoretical data rates.

Setting	Average Data Throughput (Mbps) in the 802.11g Data Rates											
	1	2	5.5	6	9	11	12	18	24	36	48	54
Conc.1600 WEP 128-bit	0.72	1.38	3.40	3.78	5.31	5.88	6.95	8.82	10.14	15.07	16.40	16.60
Conc. 4000 No WEP	0.75	1.45	3.55	3.93	5.49	6.44	7.22	9.64	11.33	16.43	18.40	18.96

Table 16. The 802.11g Average Data Throughput Results in the Suburban Area

The overall 802.11g performance results in the suburban area are presented in Table 17. The maximum data link rate at the distance of 3,100 m using the 13.5 dBi external antennas was 11 Mbps and the achievable data throughput was around 6 Mbps.

Distance (m)	Max. 802.11g Data Rate (Mbps)	Maximum Achievable Data Throughput (Mbps)		Average PER (%)		Average Received Signal Strength (dBm)	
		Conc. 1600 WEP 128-bit	Conc. 4000 No WEP	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP	DSSS Data Rates	OFDM Data Rates
400	54	19.62	23.61	2.40	1.80	−45.69	−51.43
1000	54	18.06	21.29	2.94	2.63	−57.28	−61.56
1600	54	12.12	11.99	4.78	4.23	−60.60	−65.32
2000	24	9.78	11.08	5.67	5.15	−61.73	−66.95
2400	24	5.59	5.68	9.73	9.09	−64.41	−70.29
3100	11	5.90	6.27	8.14	7.65	−62.05	−68.36

Table 17. Overall 802.11g Performance Results in the Suburban Area

In Figure 19, there is a graphical representation of the average data throughput results in the 802.11g data link rates. As a final point, Figure 20 illustrates the decrease in the maximum achievable data throughput of the 802.11g WLAN as the distance, during the field measurements, increased.

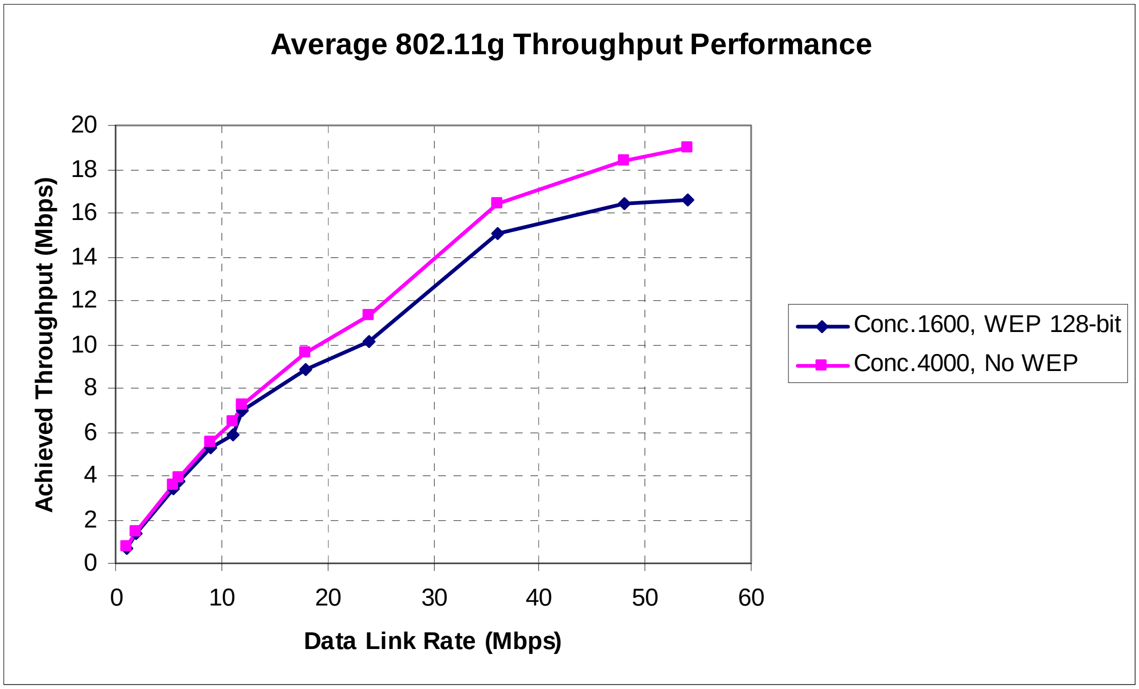

Figure 19. Average 802.11g Throughput Performance in the Suburban Area

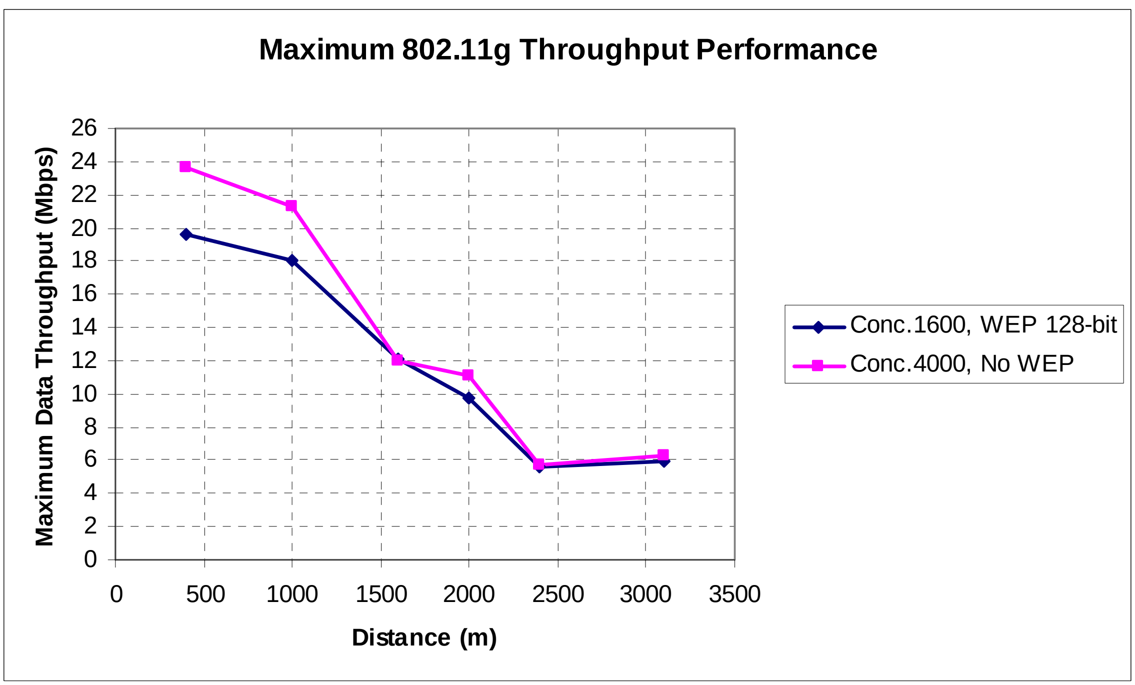

Figure 20. Maximum 802.11g Throughput Performance in the Suburban Area

C. MEDIUM DENSITY VEGETATION MEASUREMENTS

The second operational environment that was chosen for the conduction of measurements was a medium-size density vegetation site at Fort Ord. This environment was deliberately chosen in order to examine the effect of vegetation in the received signal strength and in the generally overall performance of the 802.11g signals under non-LOS conditions.

The bridges were again mounted on two masts at a height of approximately two meters and two 10 dBi Yagi antennas were selected for transmitting and receiving the 802.11g signals. Since all the selected points in the vegetation site did not provide a clear LOS, these antennas were preferred because their beam width was larger than that of the 13.5 dBi Yagi antennas that were used in the previous environment, and hence, the alignment (although not practically possible for a non-LOS case) was relatively more successful and easier to come about.

The medium vegetation site where the measurements were taken place is shown in Figure 21.

Figure 21. Medium Vegetation Site at Fort Ord

1. Overall Actual Data Throughput Performance

The measurements were done using the same 22 Mbytes transfer file and the same two settings for the bridges as before so as to have a common base for comparisons. The derived throughput results for the different distances from the root bridge are presented in Table 18.

Distance (m)	Setting	Actual Data Throughput (Mbps) in the 802.11g Data Rates (Mbps)											
		1	2	5.5	6	9	11	12	18	24	36	48	54
25	Conc.1600 WEP 128-bit	0.68	1.46	3.53	4.16	6.48	6.39	8.42	11.69	14.14	18.69	21.99	23.12
	Conc.4000 No WEP	0.73	1.45	3.56	4.3	6.69	6.99	8.67	11.56	14.91	21.29	23.27	25.07
60	Conc.1600 WEP 128-bit	0.68	1.32	3.34	3.85	5.7	6.13	7.27	10.24	12.54	16.01	18.93	19.15
	Conc.4000 No WEP	0.65	1.3	3.61	3.99	5.2	6.33	7.07	9.99	12.74	17.12	20.62	19.62
85	Conc.1600 WEP 128-bit	0.57	1.25	3.12	3.78	5.04	5.73	6.57	8.02	11.03	14.05	NA	NA
	Conc.4000 No WEP	0.58	1.26	3.25	3.68	5.29	5.89	6.87	8.41	11.21	14.99	NA	NA
110	Conc.1600 WEP 128-bit	0.44	1.05	3.04	3.49	4.46	5.67	6.09	5.79	NA	NA	NA	NA
	Conc.4000 No WEP	0.43	1.04	3.05	3.53	4.55	6.05	6.28	6.12	NA	NA	NA	NA

Table 18. Overall Throughput Results in Medium Vegetation Environment

Even though there was no LOS between the root and the non-root bridges, the high data link rates were maintained until the distance of 60 m. At the distance of 85 m, association could not be established for the data rates of 48 and 54 Mbps, while at 110 m the same was observed from 24 Mbps and above. Therefore, in this case, the non-LOS conditions and the medium vegetation drastically affected the actual throughput performance of the 802.11g WLAN, especially for the data rates above 18 Mbps, as the distance increased only a few tens of meters. Of course, this environment also affected the results for the average PER and the received signal strength. Figures 22 and 23 illustrate the

throughput performance for the two settings that were used. The highest values that were achieved ranged between 23 and 25 Mbps at the distance of 25 meters.

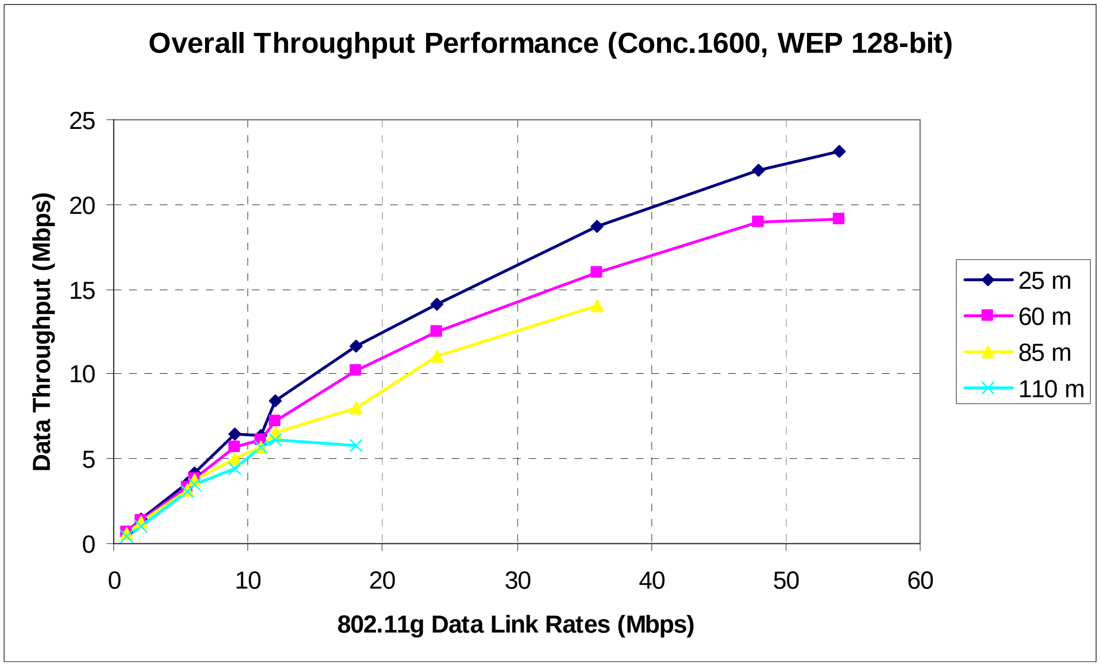

Figure 22. Overall Throughput Performance in Medium Vegetation Environment (Conc. 1600, WEP 128−bit)

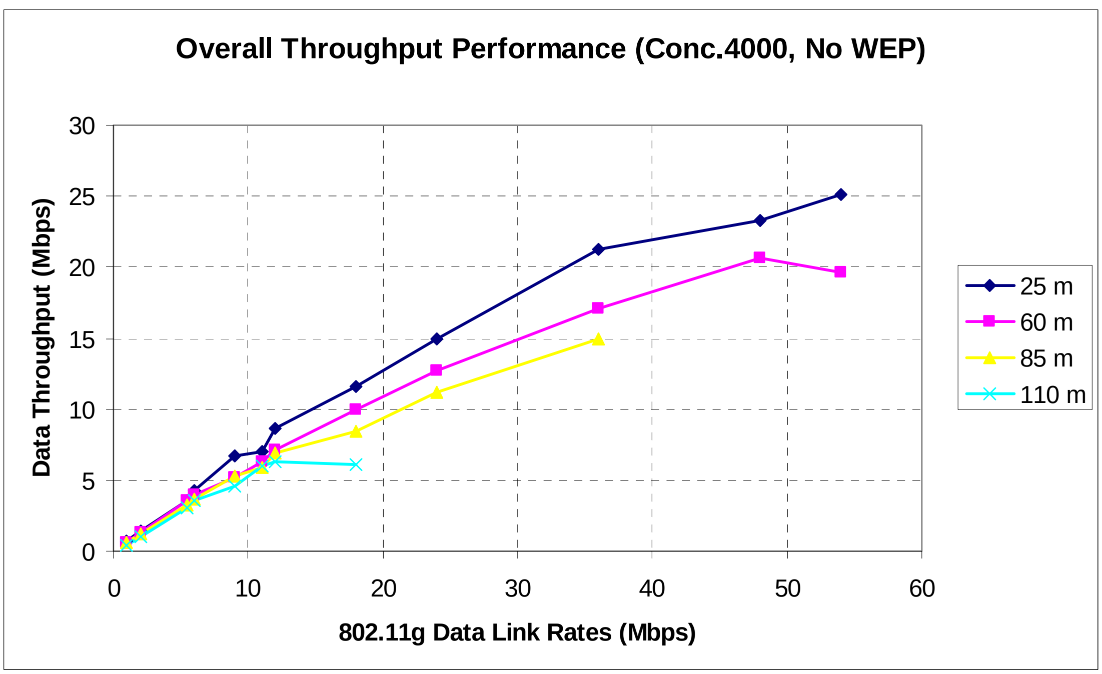

Figure 23. Overall Throughput Performance in Medium Vegetation Environment (Conc. 4000, No WEP)

2. Overall PER Performance

The PER results for the medium vegetation environment are tabulated in Table 19. It is interesting to note that at the distance of 25 m the PER was below 1% and for the longer distances it increased rather rapidly. This fact justifies the reduced throughput results that were observed at 85 and 110 m. Figure 24 depicts the measured results and shows the small difference in the PER between the two settings.

Distance (m)	Average PER (%)	
	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
25	0.60	0.57
60	4.04	3.54
85	5.39	5.12
110	7.89	7.56

Table 19. Overall PER Results in Medium Vegetation Environment

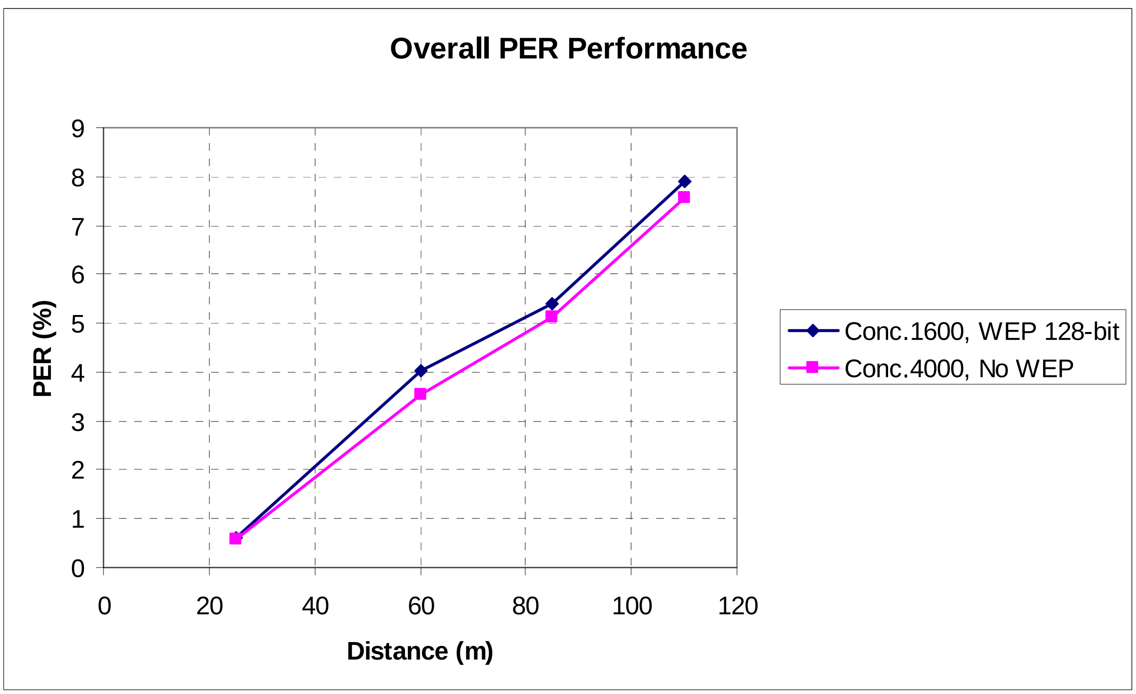

Figure 24. Overall PER Performance in Medium Vegetation Environment

3. Overall Received Signal Strength Performance

The vegetation environment significantly affected the received signal strength. The derived results indicated an extreme degradation as the distance increased only

25−35 meters each time. The average calculated received signal strength at the distance of 110 m was approximately −80 dBm for the DSSS data rates and −87 for the OFDM data rates, values which are absolutely worse than the corresponding values at the distance of 3,100 m in the urban area environment that was described earlier. Table 20 contains the minimum and the maximum values that were achieved as well as the average values that were calculated applying the same method as before. The graphical representation of the measured results is shown in Figure 25.

Distance (m)	Received Signal Strength (dBm)					
	DSSS Data Rates			OFDM Data Rates		
	Min	Max	Average	Min	Max	Average
25	−49	−47	−47.57	−56	−54	−55.30
60	−67	−64	−64.86	−73	−69	−69.91
85	−73	−71	−71.83	−79	−76	−77.49
110	−82	−79	−80.36	−89	−86	−87.12

Table 20. Overall Received Signal Strength Results in Medium Vegetation Environment

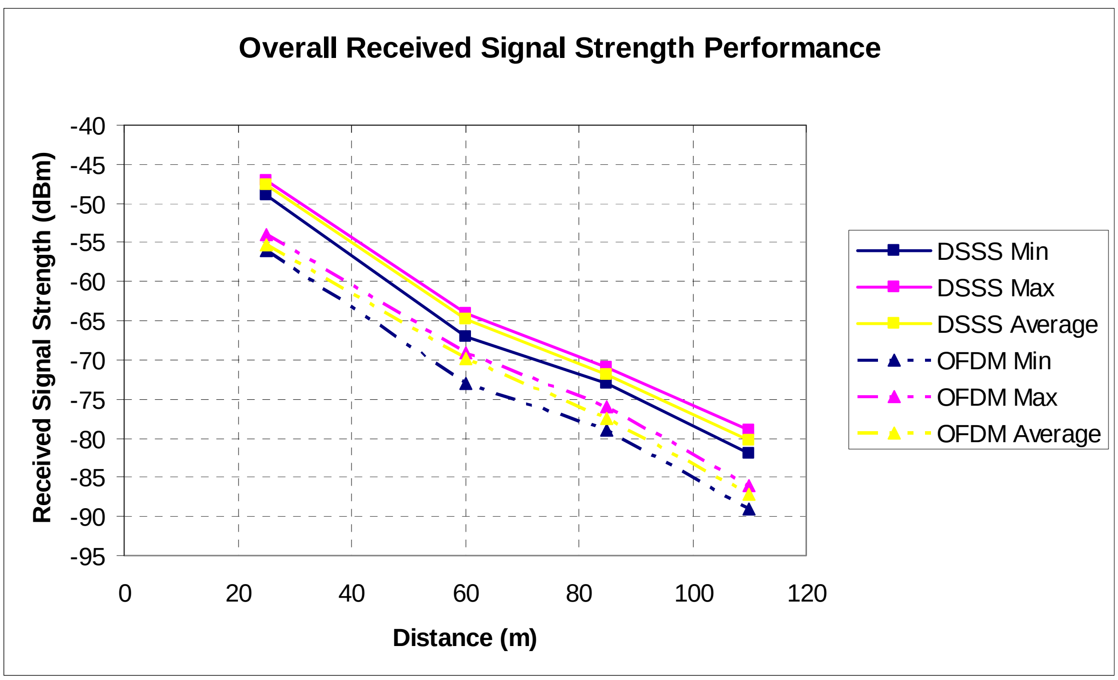

Figure 25. Overall Received Signal Strength Performance in Medium Vegetation Environment

4. Summary of the Results in the Medium Vegetation Environment

The average data throughput results for each of the 802.11g data link rates were calculated by combining the collected data in Table 18; the results are summarized in Table 21. Note that the results above 36 Mbps seem to be higher than those in the urban area; the truth is that they were derived at distances very close to the root bridge (25−85 meters). For the same data rates, although the root and the non-root bridges were very close, the achieved data throughput was always below 50% of the corresponding theoretical data rates. Figure 26 illustrates the average data throughput performance in this environment.

Setting	Average Data Throughput (Mbps) in the 802.11g Data Rates											
	1	2	5.5	6	9	11	12	18	24	36	48	54
Conc. 1600 WEP 128-bit	0.59	1.27	3.26	3.82	5.42	5.98	7.09	8.93	12.57	16.25	20.46	21.13
Conc. 4000 No WEP	0.60	1.26	3.37	3.87	5.43	6.31	7.22	9.02	12.95	17.80	21.94	22.34

Table 21. The 802.11g Average Data Throughput Results in the Medium Vegetation Environment

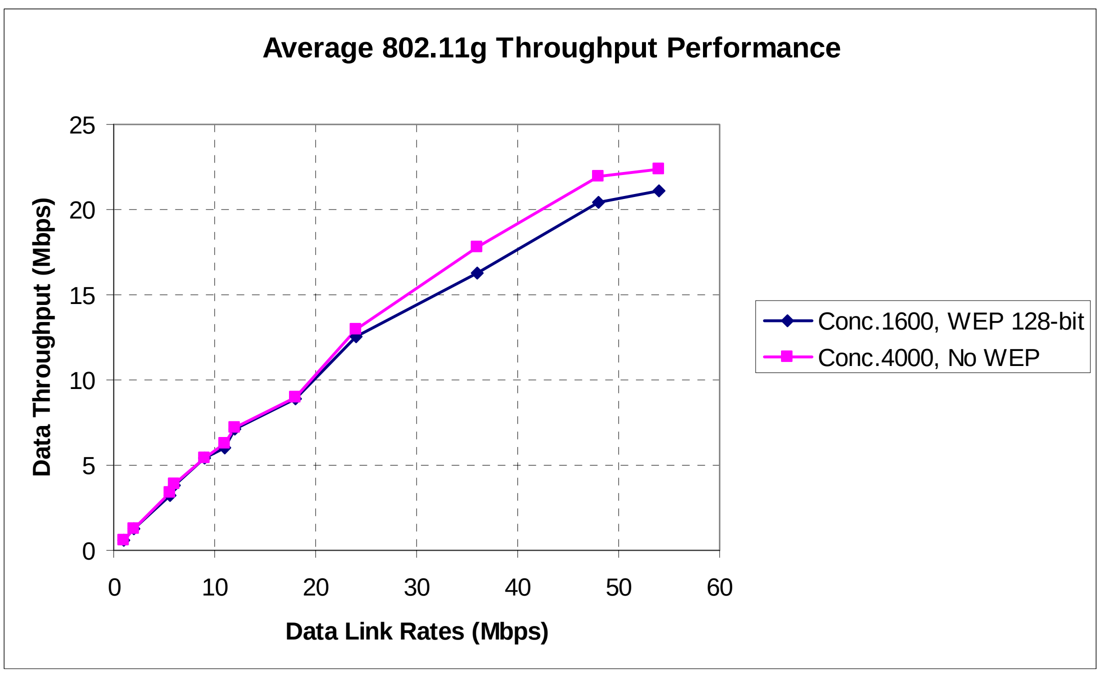

Figure 26. The 802.11g Average Data Throughput Performance in Medium Vegetation Environment

From Figure 26, it can also be observed that both settings performed almost the same from 1 Mbps until 24 Mbps. For the higher data rates, concatenation 4000 without WEP showed a slight superior performance.

The overall performance of the 802.11g WLAN in the medium vegetation environment is summarized in Table 22.

Distance (m)	**Max. 802.11g Data Rate (Mbps)**	**Maximum Achievable Data Throughput (Mbps)**		**Average PER (%)**		**Average Received Signal Strength (dBm)**	
		Conc. 1600 WEP 128-bit	**Conc. 4000 No WEP**	**Conc. 1600 WEP 128-bit**	**Conc. 4000 No WEP**	**DSSS Data Rates**	**OFDM Data Rates**
25	54	23.12	25.07	0.60	0.57	−47.57	−55.30
60	54	19.15	19.62	4.04	3.54	−64.86	−69.91
85	36	14.05	14.99	5.39	5.12	−71.83	−77.49
110	18	5.79	6.12	7.89	7.56	−80.36	−87.12

Table 22. Overall 802.11g Performance Results in the Medium Vegetation Environment

As can be seen, at 110 m, the maximum data link rate at which association was achieved between the two bridges, using the 10 dBi Yagi antennas, was 18 Mbps, and the actual throughput was around 6 Mbps. The final conclusion is that the medium vegetation environment, where the measurements were taken with no LOS conditions, negatively influenced the overall performance of the 802.11g WLAN. It was observed that 110 m away from the root bridge, the derived results were similar or worse to the results at a distance of 3,100 m in the urban area of the city of Monterey. This indicates how crucial and essential the existence of LOS conditions are for the performance of 802.11g wireless networks. However, even under these unfavorable operational conditions, the designed 802.11g WLAN performed satisfactorily in very short distances and could be used for actual military operations with success.

Figure 27 simply confirms the sudden drop in the maximum throughput as the distance between the two bridges increased only within 110 meters.

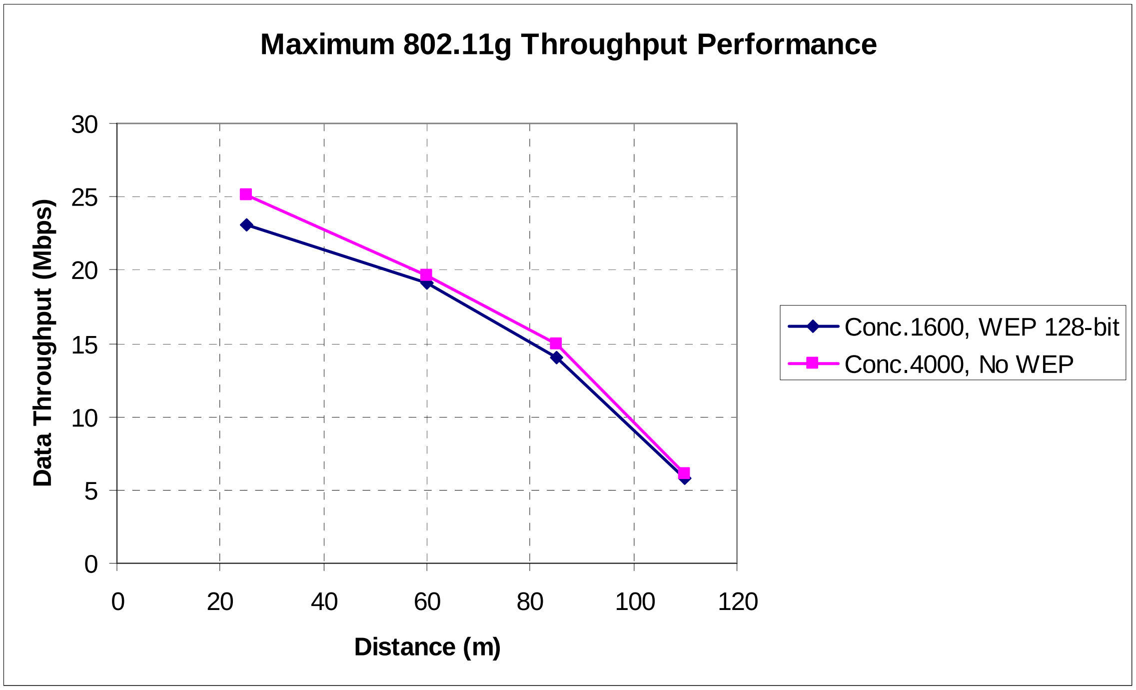

Figure 27. Maximum 802.11g Throughput in the Medium Vegetation Environment

D. COASTAL ENVIRONMENT MEASUREMENTS

The last set of measurements was conducted in a coastal environment with LOS. The root bridge was located at the dock of the Commercial Fisherman's Wharf and the non-root bridge was placed at four points along the coast of Monterey Bay with an effort to cover as much water body as possible. Figure 28 shows this environment. The bridges and the external antennas were again mounted on the same two masts as before and the effective height of the antennas was nearly the same. In order to succeed at a longer range, the Yagi 13.5 dBi antennas that had also been used for the measurements in the urban area were used.

Figure 28. Coastal Environment with LOS

1. Overall Actual Data Throughput Performance

Table 23 presents the results of the actual throughput that was achieved at the four locations. At the first point, which was only 650 m away from the root bridge, the highest value that was observed was 25.29 Mbps at the data rate of 54 Mbps for the setting with concatenation 4000. At the second test point (1800 m), although association between the bridges was achieved for the 48 and 54 Mbps data rates, the resulting throughput values were too low (the abbreviation LT in the Table means low throughput). At the third location (3000 m), the transfer of the file was aborted at the data rate of 12 Mbps, while for the rest of the data rates, association could not be established. Finally, at the distance of 3.8 km, the highest data rate that the two bridges were communicating at was 6 Mbps.

Distance (m)	Setting	Actual Data Throughput (Mbps) in the 802.11g Data Rates											
		1	2	5.5	6	9	11	12	18	24	36	48	54
650	Conc.1600 WEP 128-bit	0.79	1.57	3.90	4.50	6.23	6.54	8.21	11.24	13.54	17.69	20.09	21.14
	Conc.4000 No WEP	0.73	1.39	3.95	4.24	6.70	7.24	8.65	12.17	14.99	18.38	23.45	25.29
1800	Conc.1600 WEP 128-bit	0.70	1.44	3.65	4.24	5.12	5.56	6.33	8.77	10.17	11.48	LT	LT
	Conc.4000 No WEP	0.69	1.39	3.62	3.89	5.22	6.55	6.67	8.99	11.01	11.76	LT	LT
3000	Conc.1600 WEP 128-bit	0.77	1.52	3.28	3.63	4.80	5.80	TA	NA	NA	NA	NA	NA
	Conc.4000 No WEP	0.59	1.32	3.21	3.61	5.37	6.11	TA	NA	NA	NA	NA	NA
3800	Conc.1600 WEP 128-bit	0.63	1.27	3.32	3.84	NA	NA	NA	NA	NA	NA	NA	NA
	Conc.4000 No WEP	0.70	1.35	3.26	3.69	NA	NA	NA	NA	NA	NA	NA	NA

Table 23. Overall Throughput Results in Coastal Environment

Figures 29 and 30 graphically present the above results for each of the two settings. As in the two previous environments, the setting with concatenation 4000 and with no WEP security resulted in higher throughput values than the setting with concatenation 1600 and the WEP 128−bit security mechanism. The difference is quite obvious at the distance of 650 m and mostly affects the higher data rates, while it is less noticeable as the distance increases.

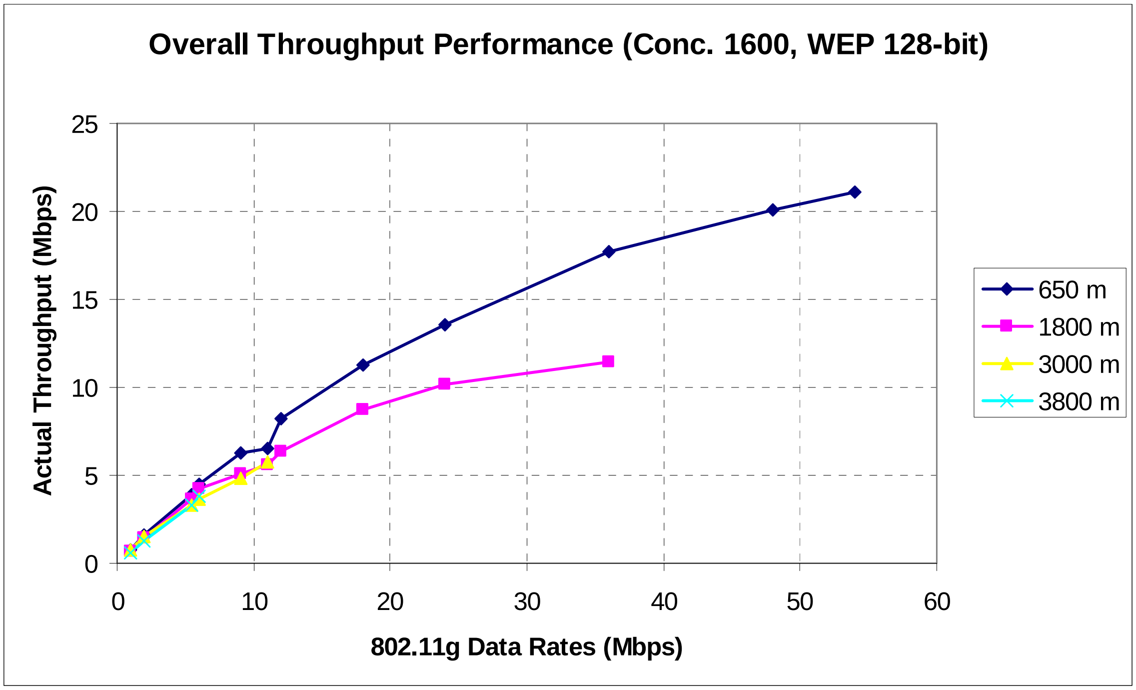

Figure 29. Throughput Performance in Coastal Environment (Conc. 1600, WEP 128−bit)

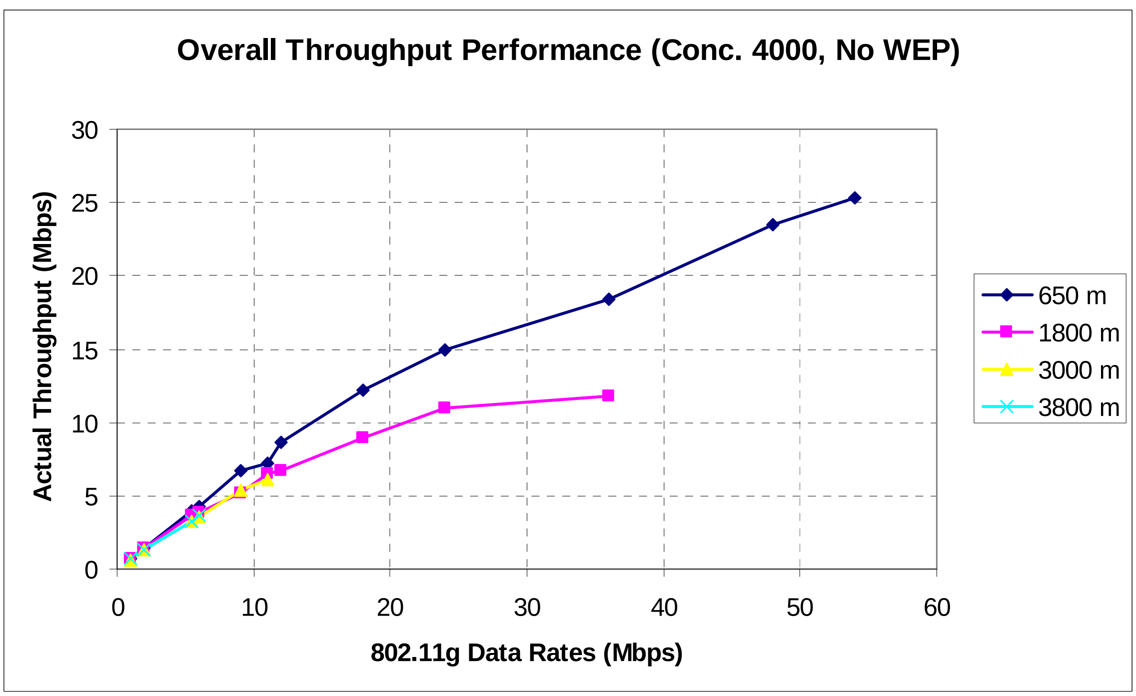

Figure 30. Throughput Performance in Coastal Environment (Conc. 4000, No WEP)

2. Overall PER Performance

The average PER results are tabulated on Table 24 and are illustrated in Figure 31. As was expected, the PER increased as the distance from the root bridge was broadened. Note that at 3.8 km the results were better than those at 3 km, and that the two settings showed almost similar performance at these distances.

Distance (m)	Average PER (%)	
	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP
650	3.54	2.86
1800	6.94	6.21
3000	13.28	13.12
3800	12.14	12.09

Table 24. Average PER Results in Coastal Environment

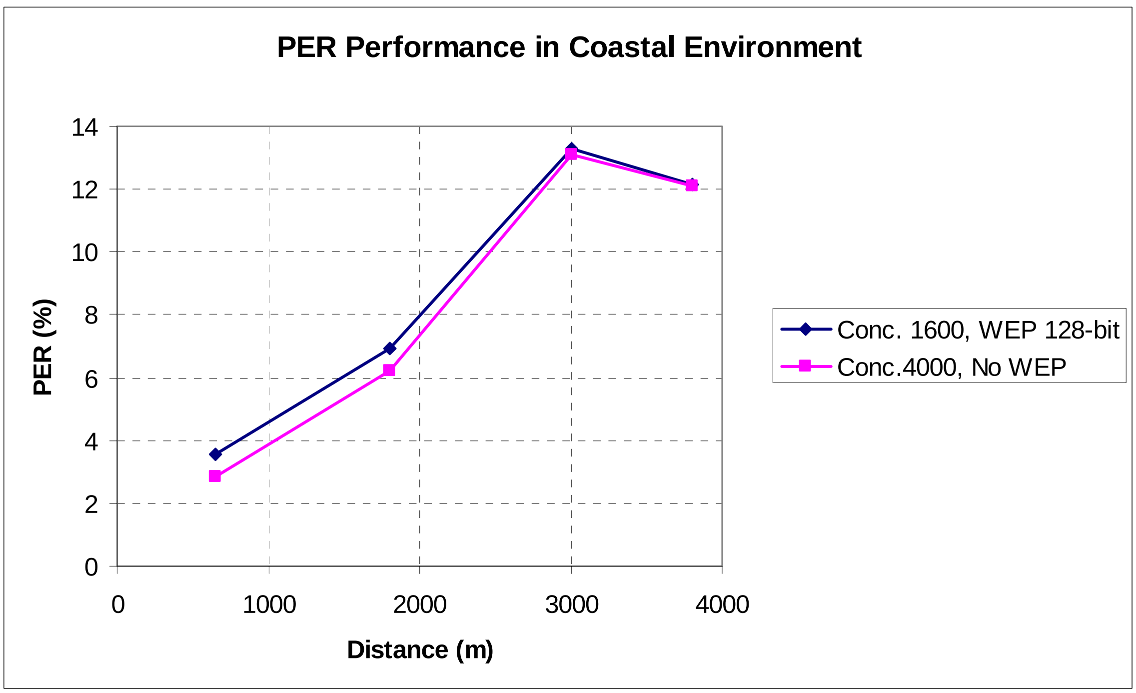

Figure 31. PER Performance in Coastal Environment

3. Overall Received Signal Strength Performance

The received signal strength performance for the 802.11g signals in the coastal environment is presented in Table 25. Figure 32 shows the graphical plot of the received signal strength that was recorded at the different locations. The interesting point is that the achieved values at 3.8 km were better than the corresponding ones at 3 km, perhaps because of the multipath characteristics of the radio channel at the given time that the collection of data took place. This fact justifies the comment about the PER at these two points that was made above.

Distance (m)	Received Signal Strength (dBm)					
	DSSS Data Rates			OFDM Data Rates		
	Min	Max	Average	Min	Max	Average
650	−44	−43	−43.39	−49	−47	−48.01
1800	−57	−56	−56.35	−64	−60	−61.61
3000	−63	−61	−62.69	−70	−66	−67.88
3800	−60	−56	−57.02	−65	−60	−62.28

Table 25. Received Signal Strength Results in Coastal Environment

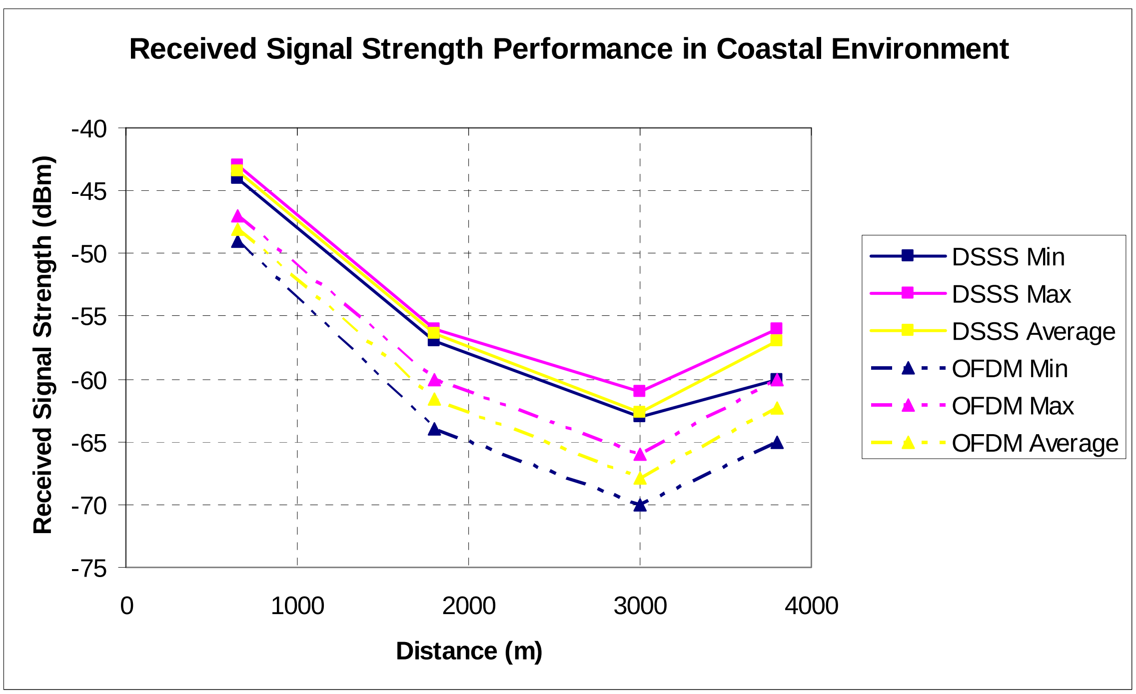

Figure 32. Received Signal Strength Performance in Coastal Environment

Figures 33 and 34 illustrate the effect of small-scale fading as it was observed at the test points that were 3 and 3.8 km from the root bridge.

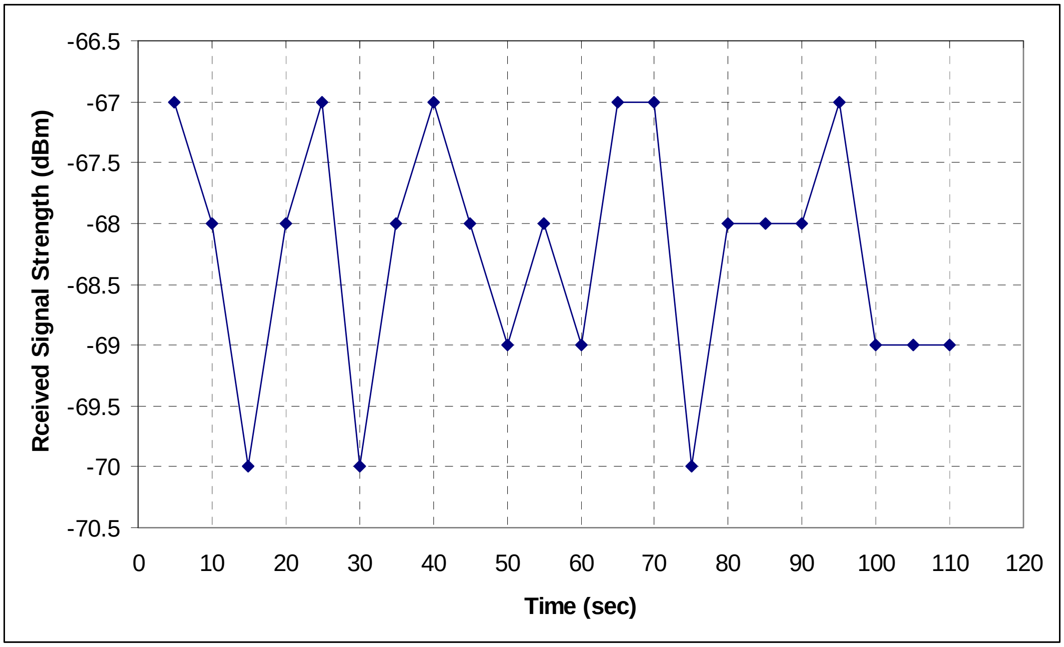

Figure 33. Small Scale Fading at 3,000 m and 9 Mbps

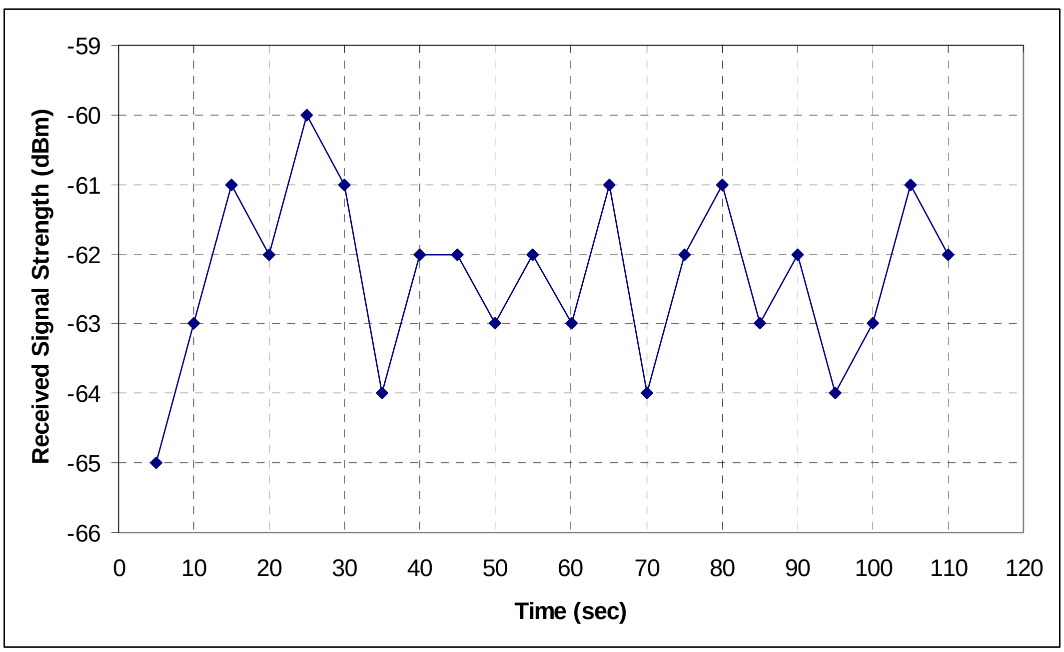

Figure 34. Small-Scale Fading at 3,000 m and 9 Mbps

4. Summary of the Results in the Coastal Environment

Table 26 summarizes the average throughput results in the 802.11g data rates at the four selected test points.

Setting	Average Data Throughput (Mbps) in the 802.11g Data Rates											
	1	2	5.5	6	9	11	12	18	24	36	48	54
Conc.1600 WEP 128	0.72	1.45	3.54	4.05	5.38	5.97	7.27	10.01	11.85	14.59	20.09	21.14
Conc.4000 No WEP	0.68	1.36	3.51	3.86	5.76	6.63	7.66	10.58	13.00	15.07	23.45	25.29

Table 26. Average Throughput Results in Coastal Environment

Figure 35 shows the average throughput results for the two wireless bridges at each of the two settings. From this figure it can be seen that both settings resulted in similar performance for the data rates up to 18 Mbps. For the rest of the 802.11g data rates, the setting with concatenation 4000 performed better. However, the average value for the data rates of 18, 24 and 36 Mbps was calculated from two test points, whereas the average value for the data rates of 48 and 54 Mbps was derived from only the nearest test point.

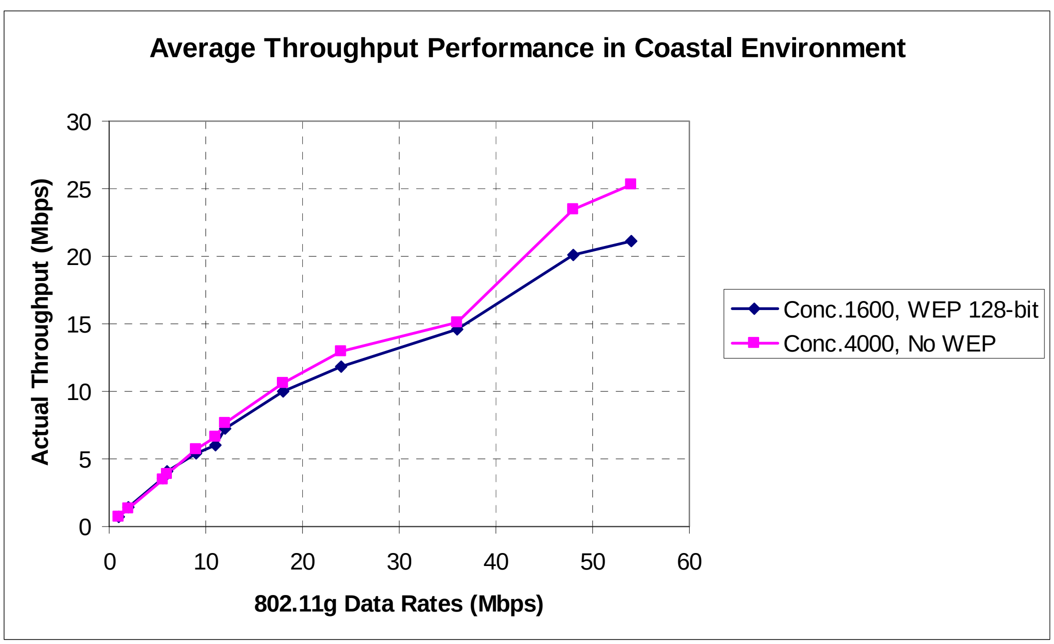

Figure 35. Average Throughput Performance in Coastal Environment

The overall 802.11g performance in the coastal environment is summarized on Table 27. At the distance of 3.8 km, the maximum throughput value that was recorded was around 3.7 Mbps in the data link rate of 6 Mbps. Figure 36 illustrates the reduction of the maximum achievable throughput as the distance increased.

Distance (m)	Max. 802.11g Data Rate (Mbps)	Maximum Achievable Data Throughput (Mbps)		Average PER (%)		Average Received Signal Strength (dBm)	
		Conc. 1600 WEP 128-bit	Conc. 4000 No WEP	Conc. 1600 WEP 128-bit	Conc. 4000 No WEP	DSSS Data Rates	OFDM Data Rates
650	54	21.14	25.29	3.54	2.86	−43.39	−48.01
1800	36	11.48	11.76	6.94	6.21	−56.35	−61.61
3000	11	5.80	6.11	13.28	13.12	−62.69	−67.88
3800	6	3.84	3.69	12.14	12.09	−57.02	−62.28

Table 27. Overall 802.11g Performance Results in Coastal Environment

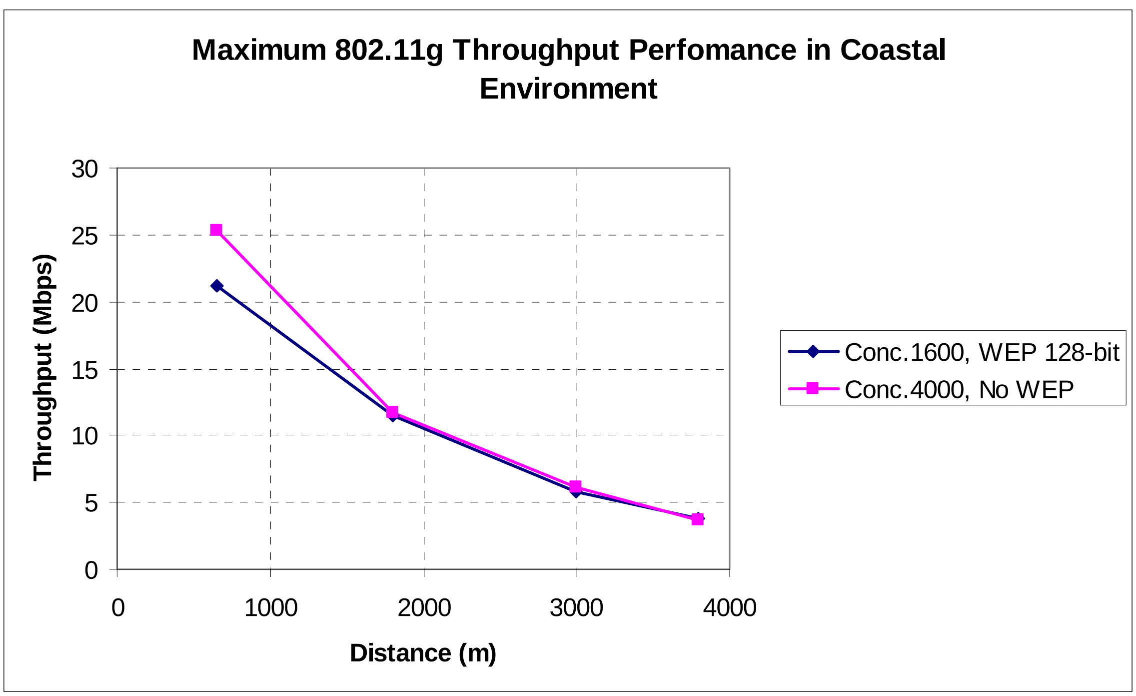

Figure 36. Maximum Throughput Performance in Coastal Environment

E. PERFORMANCE SUMMARY UNDER THE THREE OPERATIONAL ENVIRONMENTS

Table 28 summarizes all the average throughput results that were derived in each of the three different environments. The results show that for the data rates up to 18 Mbps, the achieved throughput was at least 50% of the corresponding 802.11g data rates. For the higher data rates, the deviation from the theoretical 802.11g rates is approximately in the range of 60-70%. As was already mentioned, concatenation 4000 with no WEP security mechanism seemed to succeed with higher data throughputs most of the time. This agrees with the description that Cisco provides for the wireless packet concatenation feature.

802.11g Data Rates	Average 802.11g Data Throughput					
	Suburban Area		Medium Density Vegetation		Coastal Environment	
	Conc.1600 WEP 128-bit	Conc.4000 No WEP	Conc.1600 WEP 128-bit	Conc.4000 No WEP	Conc.1600 WEP 128-bit	Conc.4000 No WEP
1	0.72	0.75	0.59	0.60	0.72	0.68
2	1.38	1.45	1.27	1.26	1.45	1.36
5.5	3.40	3.55	3.26	3.37	3.54	3.51
6	3.78	3.93	3.82	3.87	4.05	3.86
9	5.31	5.49	5.42	5.43	5.38	5.76
11	5.88	6.44	5.98	6.31	5.97	6.63
12	6.95	7.22	7.09	7.22	7.27	7.66
18	8.82	9.64	8.93	9.02	10.01	10.58
24	10.14	11.33	12.57	12.95	11.85	13.00
36	15.07	16.43	16.25	17.80	14.59	15.07
48	16.40	18.40	20.46	21.94	20.09	23.45
54	16.60	18.96	21.13	22.34	21.14	25.29

Table 28. Average Data Throughput Results in All Environments

A last comment about the above results has to do with the fact that the throughput values for the 48 and 54 Mbps data rates are higher in the medium density vegetation as well as in the coastal environment. As far as the vegetation environment is concerned,

these results were obtained from two measurements very close to the root bridge. For the coastal case, these results were derived only from the first test point, which was 650 m away from the root bridge. Based on this, it would not be correct to conclude that these two environments resulted in higher data throughputs than the suburban area environment for the data rates of 48 and 54 Mbps.

Table 29 summarizes the 802.11g performance as it was achieved under the different environmental conditions.

Environment	**Distance (m)**	**Max. 802.11g Data Rate (Mbps)**	**Max. Data Throughput (Mbps)**		**Average PER (%)**		**Average Received Signal Strength (dBm)**	
			Conc. 1600 WEP 128	**Conc. 4000 No WEP**	**Conc. 1600 WEP 128**	**Conc. 4000 No WEP**	**DSSS Data Rates**	**OFDM Data Rates**
Suburban Area	400	54	19.62	23.61	2.40	1.80	−45.69	−51.43
	1000	54	18.06	21.29	2.94	2.63	−57.28	−61.56
	1600	54	12.12	11.99	4.78	4.23	−60.60	−65.32
	2000	24	9.78	11.08	5.67	5.15	−61.73	−66.95
	2400	24	5.59	5.68	9.73	9.09	−64.41	−70.29
	3100	11	5.90	6.27	8.14	7.65	−62.05	−68.36
Medium Vegetation	25	54	23.12	25.07	0.60	0.57	−47.57	−55.30
	60	54	19.15	19.62	4.04	3.54	−64.86	−69.91
	85	36	14.05	14.99	5.39	5.12	−71.83	−77.49
	110	18	5.79	6.12	7.89	7.56	−80.36	−87.12
Coastal	650	54	21.14	25.29	3.54	2.86	−43.39	−48.01
	1800	36	11.48	11.76	6.94	6.21	−56.35	−61.61
	3000	11	5.80	6.11	13.28	13.12	−62.69	−67.88
	3800	6	3.84	3.69	12.14	12.09	−57.02	−62.28

Table 29. Overall 802.11g Performance in All Environments

It is important to notice that the best-received signal strength performance was achieved in the coastal environment with LOS conditions. In the suburban area, although the outdoor WLAN was again implemented under LOS conditions, the results were slightly worse because of the location of the selected test points and the different multi-path characteristics of the channel. Factors such as traffic from nearby people and vehicles as well as nearby buildings certainly affected the received signal strength at each point and resulted in small-scale fading. For the vegetation environment, the results were satisfactory only for very short distances from the root bridge and revealed that vegetation greatly affected the received signal strength, and consequently the overall performance of the designed WLAN.

F. SUMMARY

This chapter presented the results that were obtained during the collection of field data under three different environmental conditions. The actual 802.11g throughput, packet error rate and received signal strength were measured at different distances from the wireless root bridge in the suburban area of Monterey, a medium density vegetation environment on Fort Ord and a coastal environment along the Monterey Bay.

The next chapter refers to large-scale path loss and compares the measured path loss values with the values that derive from some of the known large scale prediction models in order to draw conclusions about the use of these models in each environment.

VI. LARGE−SCALE PATH LOSS

Large-scale propagation models are used in order to predict the received signal strength at large distances from the transmitter. This chapter presents some of these models as well as the predicted results for the path loss in each of the distances that the measurements were conducted at. Then, the predicted and measured values are compared and some comments concerning the path loss exponent in each operational environment are made.

A. OUTDOOR RADIO PROPAGATION MODELS

Three commonly used outdoor propagation models are discussed in this section. It needs to be noted that these models were selected because they match the parameters of the designed WLAN and approximate the conditions under which the measurements were performed.

1. Free Space Model

The free space propagation model is a simple theoretical model, which is used in cases when there are clear LOS conditions and no obstructions between the transmitter and the receiver. According to this model, the received power at a distance d from the transmitter is given by the Friis free space equation [2]:

$$P_r\left(d\right) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{6.1}$$

where P_r is the received power, P_t is the transmitted power, G_t and G_r are the gains of the transmitting and the receiving antennas respectively, λ is the wavelength of the signal in meters, d is the distance in meters between the transmitter and the receiver, and L is the system loss factor that has nothing to do with propagation. Notice that the received power is inversely proportional to the square of the distance that separates the transmitting and the receiving antennas.

In order to predict the signal attenuation at any distance from the transmitter, the term *Path Loss (PL)* is used. Hence, the path loss is simply the ratio of P_r to P_t, or the

difference in dB between the transmitted and the received power at a given distance, and for this model is predicted by the following formula [2]:

$$PL(\text{dB}) = 10\log\left[\frac{P_t}{P_r}\right] = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right] \tag{6.2}$$

where the antennas gains have been included for generalizing purposes. The standard definition of PL does not include the antenna gains. The negative sign has been introduced to give a positive dB value.

In Chapter II, reference was made to the fact that the propagation loss favors the 802.11g signals compared to the 802.11a signals. This can obviously now be explained from equation (6.2). For the same antenna gains and at exactly the same distance, the path loss is dependent only on the signal wavelength. The 802.11g signals, with the lower frequency of 2.4 GHz, result in a higher value of wavelength, and therefore in a lower and more favorable value for the propagation path loss. It is easy to calculate that the 802.11g specification has a path loss advantage of approximately 6.4 dB over the 802.11a specification. That is why the 2.4 GHz links (802.11 b and g) will extend further than the 5 GHz (802.11a) links.

2. Ground Reflection (Two−Ray) Model

The Two-Ray Model is another useful theoretical model that is based on geometric optics. In this case, propagation is described by considering two paths between the transmitter and the receiver: a direct path (i.e., direct wave going from the transmitter to the receiver) and a ground reflected ray of path. This model provides satisfactory results for the received signal strength over distances of several kilometers when the transmitter antennas are stationed at heights that exceed 50 m according to [2]. More so, the model can be applied in the cases where the separation distance d between transmitter and receiver satisfies the following condition [25]:

$$d \gg h_t + h_r \tag{6.3}$$

or generally when

$$d > 10\left(h_t + h_r\right) \tag{6.4}$$

where h_t and h_r are the heights of the transmitter and the receiver respectively.

The received power at a distance d from the receiver for perfectly reflecting ground (i.e., the magnitude of the ground reflection coefficient is 1) is given by [25]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}\ 4\sin^2\left(\frac{\theta_\Delta}{2}\right) \tag{6.5}$$

where θ_Δ is the phase difference between the two E – field components, which can be easily computed using the following relation [2]:

$$\theta_\Delta = \frac{2\pi}{\lambda}\frac{2h_t h_r}{d} = \frac{4\pi h_t h_r}{\lambda d} \tag{6.6}$$

Hence, from the above formula, the path loss in dB will be:

$$PL(\text{dB}) = 10\log\left[\frac{P_t}{P_r}\right] = -10\log\left[\frac{G_t G_r \lambda^2 4\sin^2\left(\frac{2\pi h_t h_r}{\lambda d}\right)}{(4\pi)^2 d^2}\right] \tag{6.7}$$

According to [2], for the special case that:

$$d > \frac{20\pi h_t h_r}{3\lambda} \approx \frac{20 h_t h_r}{\lambda} \tag{6.8}$$

the received power can be expressed as [2]:

$$P_r(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{6.9}$$

and the path loss for this case can be expressed in dB as:

$$PL(\text{dB}) = 40\log d - \left(10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r\right) \tag{6.10}$$

Equations (6.8) and (6.9) imply that, at large distances, the received power does not depend on the radio frequency as in the case of the free space model. Moreover, it is inversely proportional to the fourth power of the distance, which means that the calculated path loss using the Two-Ray model will be higher than the corresponding one using the free space model.

3. Okumura Model

This model is mainly used for the path loss prediction in urban areas. It is based exclusively on measured data and can be applied for the following parameters [2]:

- Frequency Range: 150 MHz - 1920 MHz but it is typically extrapolated up to 3000 MHz.
- Distance Range: 1 km – 100 km.
- Transmitter Antenna Height Range: 30 m – 1000 m.

According to this model, the median value of propagation path loss is predicted by the following equation [2]:

$$L_{50}(\mathrm{dB}) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \quad (6.11)$$

where L_{50} is the 50th percentile value of path loss, L_F is the free space path loss, $A_{mu}(f,d)$ is the median attenuation relative to free space, $G(h_{te})$ and $G(h_{re})$ are the transmitter and receiver antenna height gain factors respectively and G_{AREA} is the gain due to the type of environment. Hence, in order to calculate the propagation path loss, initially, the free space path loss has to be estimated from equation (6.2) and then the above correction factors have to be added.

The median attenuation relative to free space can be found from the set of curves, shown in Figure 37, that were developed by Okumura in an urban area over a quasi−smooth terrain with a transmitter (base station) effective antenna height (h_{te}) of 200 m and a receiver (mobile) antenna height (h_{re}) of 3 m.

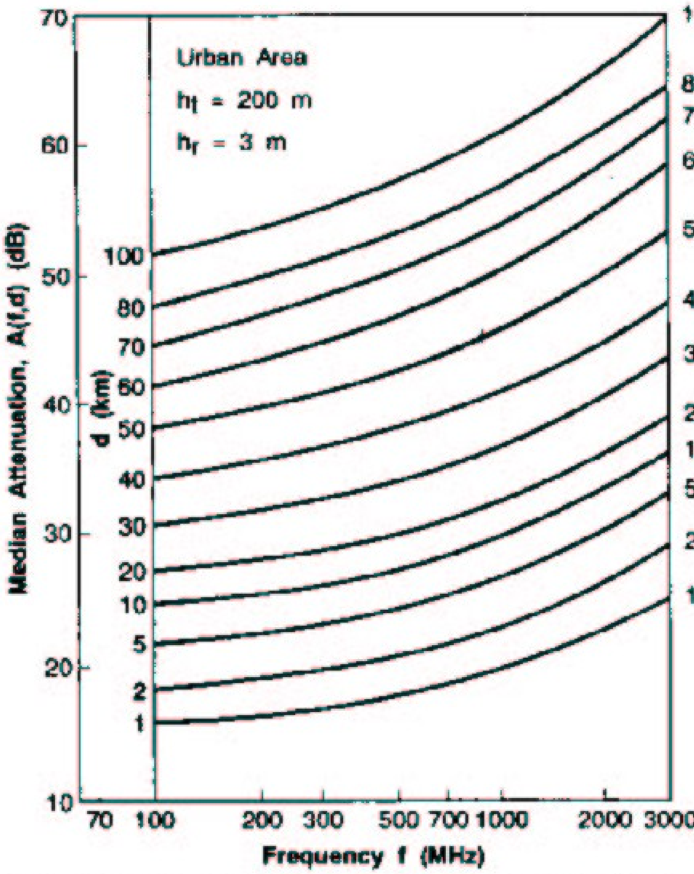

Figure 37. Median Attenuation Relative to Free Space Over a Quasi-Smooth Terrain (From Ref.2.)

The antenna height gain factors are strictly a function of height and are calculated by the following expressions [2]:

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) \quad \text{when } 30 \text{ m} < h_{te} < 1000 \text{ m} \qquad (6.12.a)$$

$$G(h_{re}) = 10\log\left(\frac{h_{re}}{3}\right) \quad \text{when } h_{re} \le 3 \text{ m} \qquad (6.12.b)$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) \quad \text{when } 3 \text{ m} < h_{re} < 10 \text{ m} \qquad (6.12.c)$$

Finally, the correction factor G_{AREA} for different types of terrain is derived from the Okumura curves shown in Figure 38.

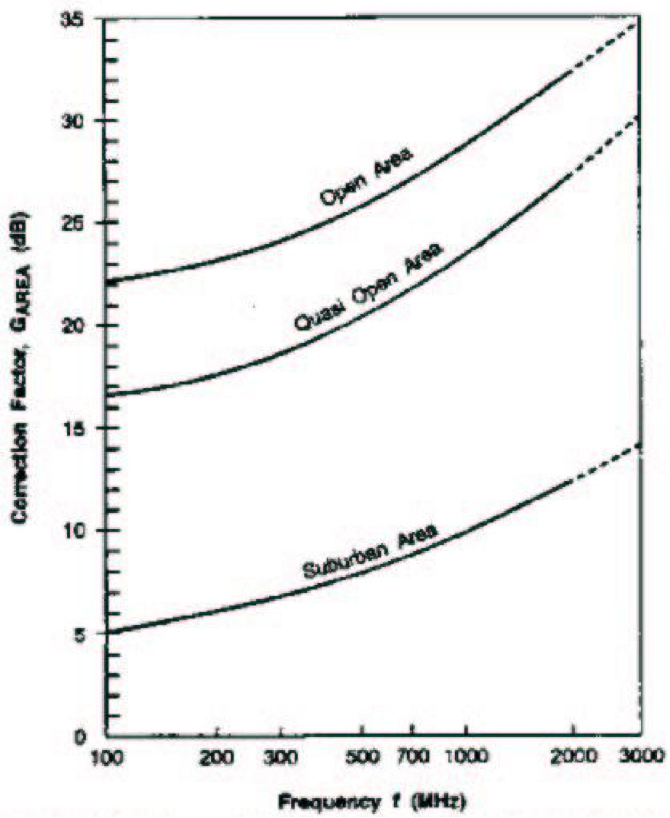

Figure 38. Correction Factor, G_{AREA}, for Different Types of Terrain (From Ref. 2.)

B. COMPARISON BETWEEN THE THEORETICAL AND MEASURED RESULTS

Since the required expressions for the calculation of the path loss have been presented, the results of these models can be compared with the results that were taken during the field measurements in each environment. To be more specific, in order to calculate the measured path loss, the following expression was used:

$$PL(\text{dB}) = 10\log\left(\frac{P_t}{P_r}\right) \tag{6.13}$$

where P_t is the transmitted power and P_r the received power. For the transmitted power, the value of 100 mW was used for the DSSS data rates and the value of 30 mW was used for the OFDM data rates. For the received power, the average received signal strength calculated at each location for the DSSS and OFDM rates was used.

1. Suburban Area

For this environment, the three models that were presented before can be applied to obtain the theoretical results. The following parameters were used for the calculations:

- $G_t = G_r = 13.5$ dBi
- $f = 2.417$ GHz (channel 2)
- $P_t = 100$ mW and $P_t = 30$ mW
- $\mathrm{h_t} = 30$ m
- $\mathrm{h_r} = 2$ m

First, equation (6.13) was used to calculate the path loss at each distance based on the field measurements. Then, the free space path loss for the six test points was found from equation (6.2). The results, of course, were different in each case. Despite the fact that the measurements took place under a LOS path, the multipath components of the urban environment affected the received signal strength, and therefore the propagation path loss. As a result, the path loss for this propagation environment could not be accurately predicted by the free space model that uses a path loss exponent, n, equal to 2. For this reason, a new path loss exponent had to be calculated that would provide more precise results. Using the measured path loss values, equation (6.2) was solved each time for n and provided six different values. The path loss values based on the field measurements as well as the six calculated values for the path loss exponent are tabulated in Table 30.

Distance (m)	Path Loss Based on Field Measurements (dB)		Calculated Path Loss Exponent (n)	
	DSSS Data Rates	OFDM Data Rates	DSSS Data Rates	OFDM Data Rates
400	65.69	66.20	2.03	2.04
1,000	77.28	76.33	2.14	2.11
1,600	80.60	80.09	2.11	2.12
2,000	81.73	81.72	2.08	2.08
2,400	84.41	85.06	2.11	2.13
3,100	82.05	83.13	1.97	2.01

Table 30. Measured Path Loss and Calculated Path Loss Exponent at Each Distance

The measured path loss results were very close for both the DSSS and the OFDM data rates. From the above values, the average value of n was 2.07 for the DSSS data rates and 2.08 for the OFDM data rates. Since the average value for both cases was almost identical, the value of 2.08 was chosen as the calculated path loss exponent for this operational environment. The modified model which could be used in order to estimate the path loss in this environment is provided by the following expression:

$$PL(\text{dB}) = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^{2.08}}\right] \qquad (6.14)$$

Figure 39 illustrates the calculated path loss exponent at each distance. It is important to note the strange behavior of n as the distance between the wireless bridges increases. The fact that n did not steadily increase with distance had to do with the location of the selected field points and the multipath characteristics of the channel during the time that the data was collected. At the 3,100 m distance, for example, the calculated path loss exponent is almost identical to the one that the free space model assumes. This could mean that at this specific location, the conditions under which the measurements were conducted at that time were ideal, and consequently resulted in a free space path loss value.

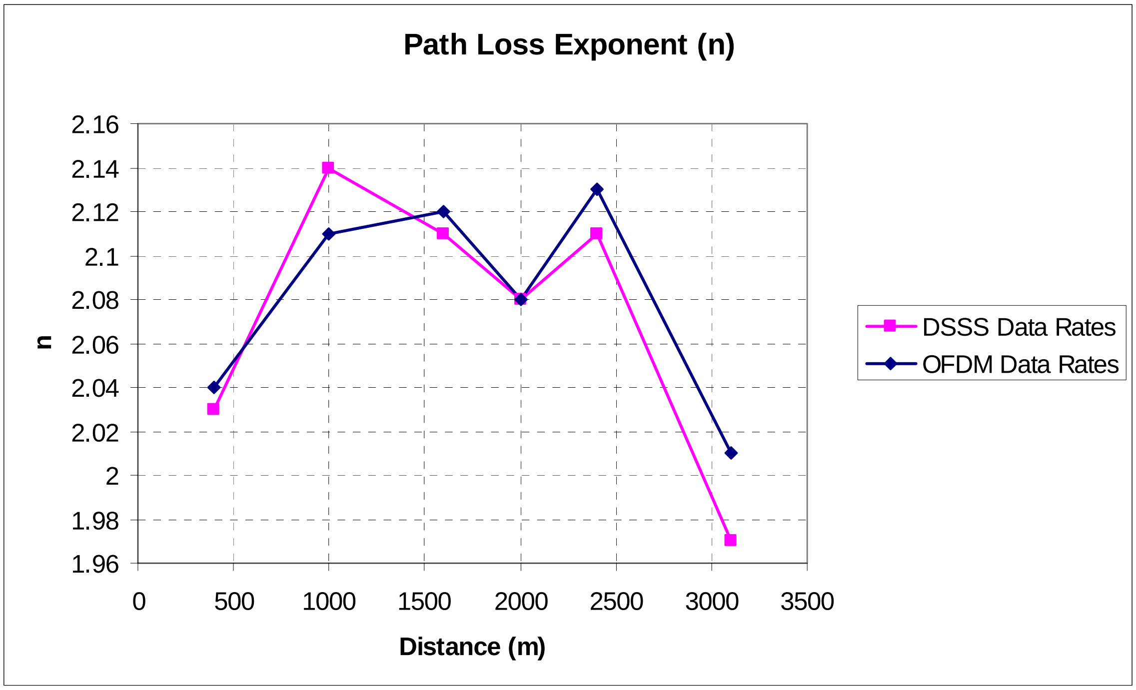

Figure 39. Calculated Values for n (Suburban Area)

The modified model of equation (6.14) was used to calculate the path loss and to compare the results with the measured values. Furthermore, the Two-Ray model and the Okumura model were used. For the calculations with the Two-Ray model, equation (6.7) was used, as equation (6.10) did not apply in the case being presented since the selected distances did not satisfy equation (6.8). As far as the Okumura model is concerned, the correction factors were calculated from the equations and the curves that were presented earlier. The following useful comment has to do with the correction factor G_{AREA} that is derived from Figure 38. According to [26, p.41], "experience with comparable measurements in the United States has shown that the typical United States suburban situation is often somewhere between Okumura's suburban and open areas." Having this in mind, it was initially decided upon to use the value derived from the open area curve for the frequency of 2,417 MHz, which is approximately 33 dB, and depending on the results, to try the value for the quasi-open area curve if necessary.

The path loss results that were measured in the field and calculated with the models described above are finally presented in Table 31 and graphically shown in Figure 40.

Distance (m)	Path Loss (dB)					
	Based on Field Measurements		Free Space Model	Modified Model	Two−Ray Model	Okumura Model
	DSSS Data Rates	OFDM Data Rates				
400	65.69	66.20	65.15	67.23	59.43	68.39
1,000	77.28	76.33	73.11	75.51	86.74	81.35
1,600	80.60	80.09	77.19	79.75	71.64	87.43
2,000	81.73	81.72	79.13	81.77	73.12	90.37
2,400	84.41	85.06	80.71	83.42	75.1	92.95
3,100	82.05	83.13	82.94	85.73	78.53	96.18

Table 31. Path Loss Results Using Different Models (Suburban Area)

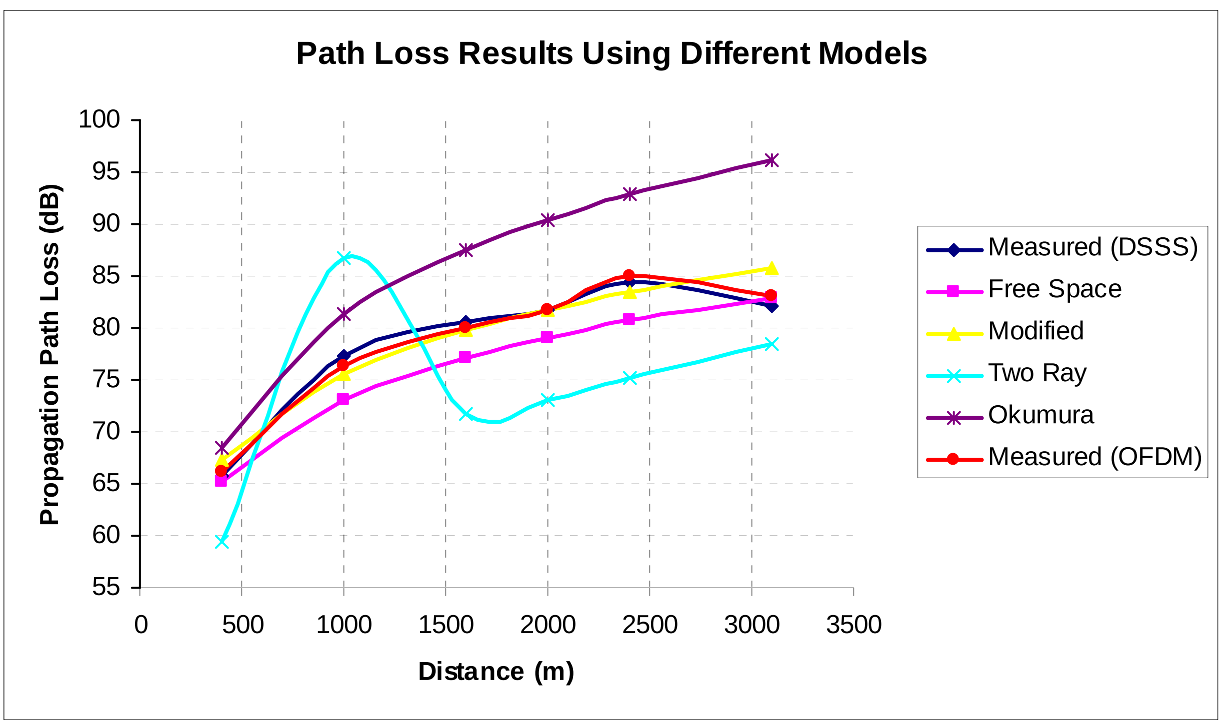

Figure 40. Comparison Among Different Propagation Models (Suburban Area)

It would be interesting to comment on the above results for each of the propagation models that were used in order to predict the path loss at the various distances, despite the fact that the collection of field data was limited to the distance of 3.1 km. First of all, the measured results revealed, as has been noted earlier, that the multipath components at the selected field points at the distance of 3,100 m added constructively to the direct path signal, perhaps because of the location of this specific point. That is why the path loss did not steadily increase as the distance between the two wireless bridges increased after 2,400 m. The modified model of equation (6.14) resulted in values that approximate quite satisfactorily the measured ones, since the maximum difference was less than 4 dB at the distance of 3,100 m.

The Okumura model also seemed to be acceptable for the suburban area of the city of Monterey. The maximum deviation from the measured values was about 14 dB and was observed at 3,100 m. According to [2], "common standard deviations between predicted and measured path loss values are around 10 dB to 14 dB." Note that these values were derived using the open area curve for the calculation of the factor G_{AREA} of this model. If instead the quasi-open area curve of Figure 38 had been used, then the obtained results would have increased by roughly 5 dB, which means that the deviation from the measured results would be greater. A last remark about this model is that it proved to be accurate for the distance of 400 m despite the fact that it is applicable for distances greater than 1,000 m.

Finally, the Two-Ray model resulted in somewhat confusing behavior for the first three distances. For all the distances except the 1,000 m distance, the predicted values were below the measured ones, whereas at 1,000 m the predicted path loss value was greater than the measured one. The most obvious explanation is that this model accurately predicts the path loss over distances of several kilometers for the case where the height of the transmitter antenna exceeds 50 m, as has been noted before. In the case being presented, the transmitter antenna height was 30 m and the maximum distance that measurements were performed at was at 3.1 km. This is probably the reason that the measured results do not closely fit the predicted ones. Also, the magnitude of the ground reflection coefficient is not actually one (i.e., not perfectly reflecting ground). This means

that assuming a smaller value for the magnitude of the ground reflection coefficient the resulting path loss equation would be different than this of equation (6.7) and would probably provide closer results. However, at 3,100 m distance, the deviation is less than 5 dB and generally speaking, for greater distances it is expected that the Two-Ray model would result in more precise path loss values.

2. Medium Vegetation Environment

For this environment, none of the previous propagation models could be applied. A modified model, based on the method previously described, was used in order to predict the path loss values. The input parameters for this case were the following:

- $G_t = G_r = 10$ dBi
- $f = 2.412$ GHz (channel 1)
- $P_t = 100$ mW and $P_t = 30$ mW

Table 32 presents the measured path loss and calculated path loss exponent for each point in the medium density vegetation environment. It can be noticed that as the distance between the two wireless bridges under non-LOS conditions increases, both the measured path loss and the calculated n progressively increase.

Distance (m)	Path Loss Based on Field Measurements (dB)		Calculated Path Loss Exponent (n)	
	DSSS Data Rates	OFDM Data Rates	DSSS Data Rates	OFDM Data Rates
25	67.57	70.07	3.40	3.58
60	84.86	84.68	3.64	3.63
85	91.83	92.26	3.72	3.74
110	100.36	101.89	3.93	4.01

Table 32. Calculated Path Loss Exponent (Medium Density Vegetation)

The average value of n was 3.67 for the DSSS data rates and 3.74 for the OFDM data rates. Therefore, the value of 3.71 (i.e., the average of the two values) was chosen as

the average calculated path loss exponent. The modified model for this operational environment is given by the following equation:

$$PL(dB) = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^{3.71}}\right] \tag{6.15}$$

The path loss results are summarized in Table 33 .The results based on the free space model are presented in order to see the large deviations from the measured values. It is also clear that the difference becomes greater as the distance increases, as at the distance of 110 m, the difference is more than 40 dB.

Distance (m)	**Path Loss (dB)**			
	Based on Field Measurements		**Based on Modified Model**	**Based on Free Space Model**
	DSSS Data Rates	**OFDM Data Rates**		
25	67.57	70.07	71.95	48.05
60	84.86	84.68	86.06	55.65
85	91.83	92.26	91.67	58.68
110	100.36	101.89	95.83	60.92

Table 33. Path Loss Results in Medium Density Vegetation Environment

The above results are illustrated in Figure 41. The modified model approximates the measured values and the maximum difference between this model and the measured values is approximately 6 dB at 110 m.

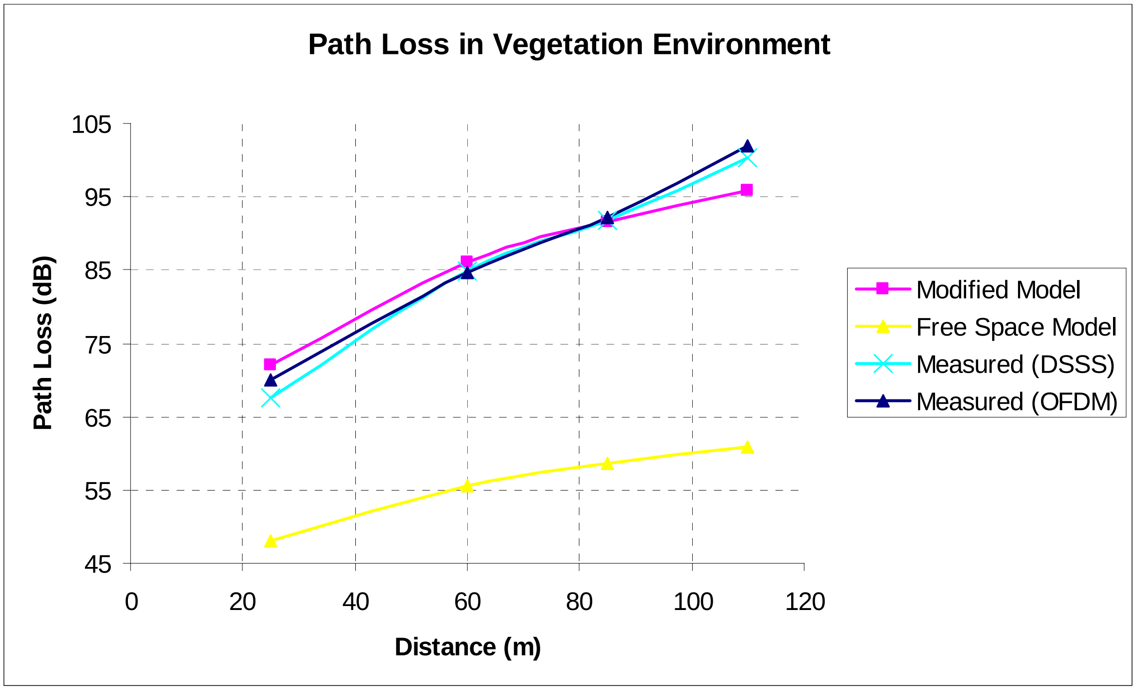

Figure 41. Comparison Among Different Propagation Models (Medium Density Vegetation Environment)

3. Coastal Environment

In this case, all the calculations were made using the following parameters:

- $G_t = G_r = 13.5$ dBi
- $f = 2.417$ GHz (channel 2) and $f = 2.427$ GHz (channel 4)
- $P_t = 100$ mW and $P_t = 30$ mW

The path loss at each distance from the wireless root bridge, based on the measured received signal strength values, is presented in Table 34. In the same table, the values of the path loss exponent that were calculated for each value of the path loss can be seen. The average value of n was found to be 1.88 for the DSSS data rates and 1.87 for the OFDM data rates. As a result, the value of 1.88 was chosen as the calculated path loss exponent for this operational environment. The modified propagation model is given by the following equation:

$$PL(\text{dB}) = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^{1.88}}\right] \qquad (6.16)$$

Distance (m)	Path Loss Based on Field Measurements (dB)		Calculated Path Loss Exponent (n)	
	DSSS Data Rates	OFDM Data Rates	DSSS Data Rates	OFDM Data Rates
650	63.39	62.78	1.79	1.76
1800	76.35	76.38	1.94	1.94
3000	82.69	82.65	2.00	2.00
3800	77.02	77.05	1.79	1.79

Table 34. Calculated Path Loss Exponent (Coastal Environment)

The path loss results based on the field measurements and two different propagation models are summarized in Table 35. Since the measured received signal strength at the distance of 3.8 km was better than that at 3 km, the resulting path loss at 3.8 km was lower than the corresponding one at 3 km. Also note that at 3 km, the path loss that was calculated was identical to the free space path loss for this distance.

Distance (m)	Path Loss (dB)			
	Based on Field Measurements		Based on Modified Model	Based on Free Space Model
	DSSS Data Rates	OFDM Data Rates		
650	63.39	62.78	66.03	69.40
1800	76.35	76.38	74.31	78.21
3000	82.69	82.65	78.48	82.65
3800	77.02	77.05	80.41	84.70

Table 35. Path Loss Results in Coastal Environment

Figure 42 illustrates the above results. The modified model provides results that closely approximate the measured ones for the distances up to 1.8 km and for those above 3.4 km. For distances between 1.8 km and 3.4 km, the free space model is more representative.

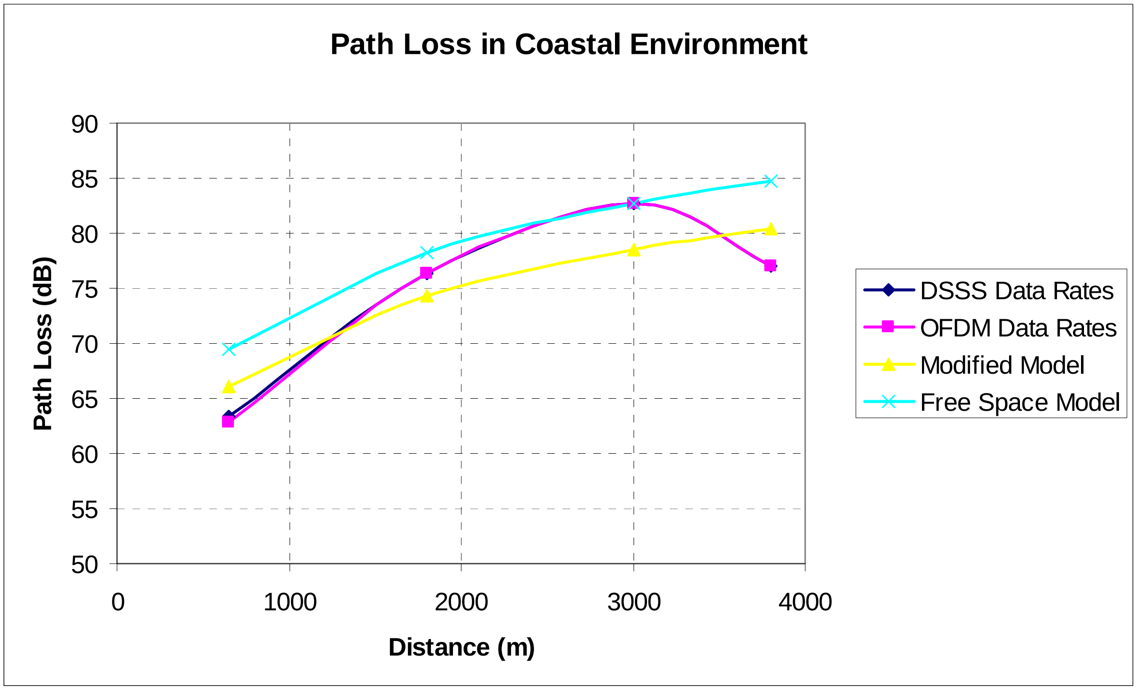

Figure 42. Comparison Among Different Propagation Models (Coastal Environment)

C. SUMMARY

In each operational scheme, the path loss was calculated at the different distances, taking into account the average values of the measured received signal strength that were presented in the previous chapter. Next, an average path loss exponent was found for each environment. The average value of *n* was 2.08 for the suburban area, 3.71 for the medium density vegetation environment and 1.88 for the coastal environment. Based on these values, the free space model was modified in each case. The result was a fairly accurate modified model that could approximate the measured values in each one of the three different propagation environments.

VII. CONCLUSIONS AND FUTURE WORK

This chapter summarizes the results of this thesis and makes suggestions for additional research that could be done in this specific area.

A. CONCLUSIONS

The outdoor point-to-point 802.11g WLAN was implemented and tested in three operational environments: a suburban area with LOS, which was represented by the city of Monterey, a medium density vegetation area with non-LOS and a coastal environment with LOS. The wireless equipment that was selected for the implementation of the network included two low-cost, commercially available portable wireless bridges from Cisco. External directional antennas were preferred so as to cover as much area as possible. In each environment, the actual 802.11g throughput, the PER and the received signal strength were recorded. The signal path loss was also calculated at each distance and was compared to the corresponding values of common outdoor propagation models. The Free Space Path Loss model was properly modified in order to obtain values that approximated the measured results in each of the three different environmental scenarios.

A larger (in size) zipped file (88 Mbytes), which was used for transferring data between the root and the non-root bridge of the wireless network, resulted in a worst PER in comparison with a file of 22 Mbytes. In the beginning, measurements were conducted at two test points using four different configurations: Concatenation 1600, Concatenation 1600 and WEP 40−bit, Concatenation 1600 and WEP 128−bit and Concatenation 4000. The results showed that the WEP security mechanisms did not significantly affect the actual throughput. The best performance in this case was achieved with the last two settings and therefore it was decided to conduct all the measurements using these settings.

According to the results in all three environments, for the 802.11g data rates up to 18 Mbps, the effective throughput was always at least 50% of the corresponding data rates. For the higher data rates, the deviation was approximately 60−70%, depending on the location. In most cases, Concatenation 4000 resulted in a slightly better throughput and PER performance in comparison to Concatenation 1600 with 128−bit WEP security. The PER generally increased with distance. The small-scale fading effect was also ob-

served during the collection of the signal strength values while some unexpected results were due to the multipath characteristics of the channel at each time that the measurements were conducted. As far as the received signal strength is concerned, it generally decreased with distance. The best values were recorded in the coastal environment, since the conditions there were more favorable than those in the suburban area environment. On the other hand, the vegetation environment and the non-LOS conditions greatly affected the received signal strength performance.

In the suburban and coastal environments, the Cisco 13.5 dBi Yagi external directional antennas were used. In the vegetation environment, the 10 dBi Yagi antenna was used. The maximum range that was achieved was 3,100 m at 11 Mbps for the suburban environment, 110 m at 18 Mbps for the vegetation environment and 3,800 m at 6 Mbps for the water environment.

For the suburban environment case, the path loss results that were calculated from the collected data satisfactorily matched the predicted results from the Free Space model and the Okumura model, but not the Two-Ray model. For the vegetation environment, the Free Space model was completely inaccurate while for the water environment it resulted in almost exact results with the measured values. Calculating an average path loss exponent for each environment, the Free Space model was modified in order to accommodate the measured path loss values. The average values for the path loss exponent were 2.08 for the suburban area, 3.71 for the medium density vegetation environment and 1.88 for the water environment.

The final conclusion is that the outdoor point-to-point 802.11g WLAN, which was implemented using two Cisco Aironet 1300 Series wireless bridges under different operational environments, could be successfully used for actual military operations or other military applications that require a flexible and durable network infrastructure. The use of higher gain antennas than those that were used in this research would certainly increase the effective throughput for the high 802.11g data rates as well as the wireless network's range, adding even more mobility and flexibility to the military needs.

B. FUTURE WORK

1. Effect of Mixed Mode Operation on the 802.11g Performance

This research presented the results of the deployed 802.11g outdoor WLAN using 802.11g stations exclusively at both ends. It would be interesting to compare these results with the ones that would be obtained if the root bridge supported both 802.11g and 802.11b stations. This mixed mode operation would certainly affect the actual throughput of the 802.11g users since the wireless bridge and the other 802.11g stations would have to use the same slot times and preamble lengths that the 802.11b stations use.

2. Employment of Multiple Antennas at the Receiver End

In order to compensate for the effects of multipath fading and improve the received signal strength and therefore the actual throughput of the WLAN, a second external antenna at the non-root bridge location could be employed, since the selected wireless bridge supports diversity.

3. Effect of Cisco TKIP and WPA TKIP Algorithms on the 802.11g Performance

The WEP 40-bit and WEP 128-bit security mechanisms that were used for the configuration of the two wireless bridges did not, in general, affect the actual throughput of the wireless network. Unless a friendly environment is assumed, enhanced security mechanisms should be applied whenever an outdoor WLAN is implemented. The employment of the Cisco TKIP and WPA TKIP algorithms as encryption mechanisms would provide important results about the actual 802.11g throughput as well as the PER in this case. A comparison with the obtained values of this research could be made to determine the efficiency of this standard under these security mechanisms.

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